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GEOTHERMAL ENVIRONMENTAL IMPACT ASSESSMENT: An Approach to Groundwater Impacts from Development, Conversion, and Waste Disposal

by

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16. ABSTRACT

Groundwater monitoring for the impacts of geothermal energy development, conversion and waste disposal is similar to groundwater monitoring for other purposes except that additional information in needed concerning the geothermal reservoir. The research described here developed a six-step methodology including failure analysis and computer-based contaminant transport and geochemical models to design groundwater monitoring plans. Failure data analyses indicate that production and injection wells have the highest probability of failure and should be the focal points for groundwater monitoring. Groundwater monitoring techniques fall into four categories: 1) monitoring the injection/production well, 2) monitoring in the saturated zone, 3) monitoring in the unsaturated zone, and 4) monitoring on or above the ground surface. Location of the monitoring wells and what to measure in them may be determined with the aid of computer contaminant transport and geochemical models. POLLUTE is a nondispersing contaminant transport groundwater computer model that enables the user to locate a contaminant plume at a given time. Prediction of resultant fluid chemistries from a leaked geothermal fluid may be essential to unambiguous evaluation of geothermal fluid impact at remote groundwater monitoring sites.

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ABSTRACT

Groundwater monitoring for the impacts of geothermal energy development, conversion and waste disposal is similar to groundwater monitoring for other purposes except that additional information is needed concerning the geothermal reservoir. Groundwater monitoring guidelines for geothermal development have been developed by Weiss, Coffey and Williams (1979). The research described here used those guidelines as a base and refined the six-step methodology to include failure analysis and computer-based contaminant transport and geochemical models.

Failure data analyses indicate that production and injection wells have the highest probability of failure and should be the focal points for groundwater monitoring. Groundwater monitoring techniques fall into four categories: 1) monitoring the injection/production well, 2) monitoring in the saturated zone, 3) monitoring in the unsaturated zone, and 4) monitoring on or above the ground surface. Monitoring the injection/production wells can best be accomplished by borehole geophysics and measurements of annulus fluid properties. Techniques include acoustic borehole televiewers, flow meters, cement logs, conductivity probes, temperature probes, and pressure gauges. Monitoring in the saturated and unsaturated zones generally will involve the use of monitoring wells in which chemical and physical measurements can be made, water samples collected, or borehole geophysics run. Location of the monitoring wells and what to measure in them may be determined with the aid of computer contaminant transport and geochemical models.

Monitoring on or above the surface includes tests on surface equipment, surface water measurements, surface geophysics and remote sensing. Surface geochemistry techniques such as radon and mercury detectors may have monitoring applications.

POLLUTE is a nondispersing contaminant transport groundwater computer model which can be applied to an anisotropic aquifer that is bounded by impermeable and/or equal potential boundaries. The location distribution coupled with the isochron distribution output from POLLUTE enables the user to locate a contaminant plume at a given time. The well flow distribution enables the user to determine under a given scenario which well will be contaminated, how much contaminant will be intercepted, and how long it will take for the well to become contaminated.

There are, for any given geothermal system, five possible geochemical mechanisms by which leaked geothermal fluid chemistries might be altered. Four of the five mechanisms are related to solution and precipitation reactions resulting from: 1) aqueous redox potential changes, 2) temperature changes, 3) pressure change effect on dissolved gases, and 4) exposure of fluids to new mineral assemblages. The fifth mechanism involves cation exchange reactions. Prediction of resultant fluid chemistries may be essential to unambiguous evaluation of geothermal fluid impact at remote groundwater monitoring sites.

Illustrative examples have been run to demonstrate the first four steps of the six-step methodology. Results indicate that the key to groundwater monitoring is to continuously measure physical and chemical characteristics of injection fluids in the production and injection wells. That should yield the first indication of leaks into the groundwater system. At most sites the immediate groundwater systems are naturally impacted by the geothermal fluid. Thus monitoring wells will normally be used to assess the impacts of a leak rather than act as the detector of a leak.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ADI -- Alternating Direction Implicit
ARS -- Arizona Revised Statutes
AWPCL -- Arizona Water Pollution Control Law
BLM -- Bureau of Land Management
CEC -- cation exchange capacity
CRS -- Colorado Revised Statutes
CFR -- Code Federal Registar
CWQA -- Colorado Water Quality Act
DEP -- Division of Environmental Protection (Nevada)
DEQ -- Department of Environment Quality (Oregon)
DEQ -- Department of Environment Quality (Wyoming)
DGMI -- Department of Geology and Mineral Industries (Oregon)
DHW -- Department of Health and Welfare (Idaho)
DOE -- Department of Energy
DOOG -- Division of Oil and Gas (California)
DWR -- Department of Water Resources (Idaho)
DWR -- Department of Water Resources (Oregon)
DWR -- Department of Water Resourses (Texas)
DWR -- Department of Water Resourses (Utah)
EQ3/6 -- Geochemical Computer Program
EPA -- U.S. Environmental Protection Agency
ERDA -- United States Energy Research and Development Agency
FDM -- Finite Difference Method
FEM -- Finite Element Method

FWPCA -- The Federal Water Pollution Control Act of 1972
gm -- grams
GRA -- Geothermal Resources Act (Colorado)
GRA -- Geothermal Resources Act (Idaho)
GRA -- Geothermal Resources Act (Texas)
GROs -- Geothermal Resources Orders
GSA -- Geothermal Steam Act of 1970
GT -- Geothermal
GW -- Gigawatt
hr. -- hour
ID -- Idaho
km -- kilometers
m -- meter
meg/100g -- milliequivalents per 100 grams
MIX 2 -- Geochemical Computer Program
MOC -- Method of Characteristics
MW -- Megawatt
MWH -- Megawatt hour
NM -- New Mexico
NPDES -- National Pollution Discharge Elimination System
NRS -- Nevada Revised Statutes
OAR -- Oregon Administrative Role Compilation
OCC -- Oil Conservation Commission (New Mexico)
OGC -- Oil and Gas Commission (Arizona)
OGCC -- Oil and Gas Conservation Commission (Colorado)
ORS -- Oregon Revised Statutes
p -- probability
PHREEQE -- Geochemical Computer Program
POLLUTE -- Solute Transport Computer Model
ppm -- parts per million
RCRA -- Resource Conservation and Recovery Act of 1976
SBLC -- State Board of Land Commissioners (Wyoming)
SDWA -- Safe Drinking Water Act
SLC -- State Lands Commission (California)
SOLMNEQ -- Geochemical Computer Program

SOLUTE -- Groundwater Solute Transport Model
TDS -- Total Dissolved Solids
TRC -- Texas Railroad Commission
T/y -- Tonne Per Year
UIC -- Underground Injection Control
USDW -- Underground Sources of Drinking Water
USFS -- United States Forest Service
USGS -- United States Geological Survey
UWPCA -- Utah Water Pollution Control Act of 1981
WATEQ -- Geochemical Computer Program
WATEQF -- Geochemical Computer Program
WATEQZ -- Geochemical Computer Program
WPCC -- Water Pollution Control Council (Arizona)
WPCC -- Water Pollution Control Council (Utah)
WRCB -- Water Resources Control Board (California)
WQCC -- Water Quality Control Commission (Colorado)
WQCC -- Water Quality Control Commission (New Mexico)
WQCC -- Water Quality Control Commission (Texas)

SYMBOLS

As -- arsenic
As^{3+} -- arsenic ion
B -- boron
B^{3+} -- boron ion
Be^{2+} -- barium ion
c -- solute concentration
°C -- degrees centigrade
Ca -- calcium
Cd -- cadmium
CH_4 -- methane
Cl^- -- chloride ion
CO_2 -- carbon dioxide
Cr -- chromium
Cs -- cesium

D -- dispersion

D_L -- longitudinal dispersion

D_T -- transverse dispersion

Eh -- oxidation-reduction potential

E^o -- standard half-cell potential

F -- Faraday constant

F^- -- floride ion

Fe^{2+}, Fe^{3+} -- iron ions

H^+ -- hydrogen

H_2S -- hydrogen sulfide

HCO_3^- -- bicarbonate ion

Hg -- mercury

IAP -- ion activity product

K -- aquifer hydraulic conductivity

K_{sp} -- solubility product

K^+ -- potassium ion

K_{eg} -- equilibrium constant

K_r -- solubility product at reference temperature

Li -- lithium

Li^+ -- lithium ion

mg/l -- milligrams per liter

Mg^{2+} -- magnesium ion

Mn^{2+} -- manganese ion

n -- number of moles

Na^+ -- sodium ion

NH_3 -- ammonia

NH_4^+ -- ammonium ion

NO_3^- -- nitrate ion

O_2 -- oxygen gas

P -- prosity

P -- pressure

pH -- $-\log [H^+]$ (negative logarithm of the hydrogen ion activity)

Pb -- lead

PO_4^{3-} -- phosphate ion

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The cooperation and encouragement of Donald B. Gilmore of U.S. Environmental Protection Agency (EPA), who was the original Project Officer, is greatly appreciated. We are also indebted to Richard L. Bateman of EPA, who helped guide this project. We would like to thank William W. Woessner of the Desert Research Institute (DRI) for guiding this project during the second year. The careful reading and constructive criticisms of this report by E. Nate Cooper are greatly appreciated.

SECTION 1

INTRODUCTION

Groundwater monitoring for impacts from geothermal development, conversion, and waste disposal is similar to groundwater monitoring for other purposes except for one major difference: additional information is required concerning the geothermal reservoir. Guidelines and methodology for developing groundwater monitoring programs are given by Everett (1980). Groundwater monitoring guidelines for geothermal development have been developed by Weiss, et al. (1979). The research reported here uses Weiss, et al. (1979) guidelines as a base and refines the methodology to include the use of failure analysis and computer-based contaminant transport and geochemical models. The groundwater monitoring methodology presented here guides the design of a monitoring plan to predict and to detect changes in groundwater quality due to geothermal development.

BACKGROUND

The development of geothermal energy sources may result in adverse impacts to groundwater from the time of development through actual conversion to energy, to waste disposal. These groundwater impacts may occur in a number of ways.

Geothermal reservoirs vary widely in their geology, hydrogeology, geochemistry, and geophysical characteristics. Thus each plant site and energy use is likely to have a unique set of effluents and physical effects. However, there are many common elements to the systems. Chemical and thermal effluents may reach the groundwater reservoir by several different pathways. Gases emitted can be entrapped by precipitation, which in turn infiltrates through the soil zone where physical, geochemical, and biological reactions alter the effluent before it reaches the groundwater reservoir. Surface water effluents can infiltrate in the same manner carrying, in addition to chemical pollutants, thermal pollution which may alter types and rates of geochemical and biological reactions within the soil, unsaturated, and groundwater zones. Effluents may be directly injected into the ground where they could impact fresh groundwater supplies via leaky wells and distribution systems, as well as altering the groundwater flow system.

Pollution from geothermal operations can occur during exploration, development, production, and utilization. During the exploration, development, and construction phases, environmental impact is usually temporary and of minimal long-term consequence. However, mitigation measures are desirable for these impacts.

The main source of pollution during operation of a geothermal energy conversion facility is the geothermal fluid itself. Depending on the nature of the geothermal fluid and the design of the conversion facility, environmental impact may range from negligible to very serious. These pollutants can be classified according to types of potential environmental damage: air pollution, water pollution (surface and groundwater), solid waste pollution, noise pollution, and the potential for induced seismicity and subsidence.

Theoretically, most environmental pollution is prevented if the conversion facility is a closed system. Seismic effects and land subsidence may still be problems. In such a system, after power conversion or heat-exchange, all the fluid is injected into the reservoir in a closed loop from the production to the injection well. High cost or technical problems may make a perfectly closed loop impractical. The final extent of pollution of the atmosphere, land, and water will depend on the amount and nature of pollutants in the waste and the rate, methods, and duration of production and disposal.

The concentration and nature of pollutants in the waste are determined mainly by the chemical characteristics of the geothermal fluid. The pollutants vary widely, both in number and concentration. Geothermal waters can be entirely benign and potable or highly corrosive and saline. The fluid characteristics vary from one reservoir to another, from one well to another in the same reservoir, and with time in the same well.

The bulk of the geothermal waste fluid is hot water, either in the form of spent brine or condensate from steam. The waste water contains dissolved and suspended solids and dissolved and entrained gases. Generally, discharge of this liquid waste to surface or groundwater bodies would have an adverse impact. The preferred disposal method is injection of the spent geothermal fluid into the geothermal reservoir. In addition to isolating the geothermal waste fluid, injection provides recharge to the reservoir and may assist in control of potential subsidence and seismicity that may be induced by fluid withdrawal.

PREVIOUS WORK

This work is part of a series of Environmental Protection Agency research projects referred to as "Geothermal Environmental Impact Assessment" carried out by several organizations and individuals over the last few years. Included in this series are reports covering the following subjects:

1. Baseline Data for Four Geothermal Areas in the United States; Geonomics, Inc. - EPA-600/7-78-188.
2. Subsurface Environmental Assessment for Four Geothermal Systems; Geonomics, Inc. - EPA-600/7-78-207.
3. Groundwater Monitoring Guidelines for Geothermal Development; Weiss, R.B., T.O. Coffey, and T.L. Williams, Harding-Lawson Associates - EPA-600/7-79-218.
4. Geothermal Waste Control Technology; Harding-Lawson Associates.
5. Geothermal Resource Utilization, Waste Disposal and Regulatory Constraints: A Decision Makers Handbook; Harding-Lawson Associates.

Previous reports under the current grant are:

1. Compilation of Failure Data and Fault Tree Analysis for Geothermal Energy Conversion Systems, Miller, F.L. and D. E. Zimmerman, Desert Research Institute, Water Resources Center, (In Press).
2. Atmospheric Emissions Inventory for Geothermal Power Production Facilities Throughout the World; Reale, A. L. and R. T. Egami - EPA-600/X-83-001.
3. Geothermal Systems Failures: Implications for Groundwater Monitoring, Miller, F. L. and D. E. Zimmerman, Ground Water Monitoring Review, Spring 1982, p. 23-29.

GROUNDWATER MONITORING CONSIDERATIONS

This project sought to develop a monitoring methodology that would enable one to design a groundwater monitoring plan to predict and detect changes in groundwater quality due to geothermal resource development. It includes a philosophy of prevention as an integral component of monitoring, since groundwater degradation is many times an irreversible process (Weiss, et al., 1979). The uniqueness of the natural environment and human activities in the potential geothermal development area prevents specification of one monitoring plan that would apply to all sites. Thus the monitoring methodology is a set of guidelines.

Groundwater monitoring is conceptually straightforward. The application and interpretation, however, may be quite complicated. Recent state and Federal regulations regarding the introduction of fluids into groundwater systems specify extensive planning and analysis (see Section 5 of this report). Another publication of related interest to this report (Everett, 1980) presents guidelines and methodologies for developing and implementing groundwater quality monitoring programs. Chapters by various authors discuss such considerations as costs, data management, and disposal well systems. Hartley (1978) discusses subsurface injection and pollution control guidance for geothermal energy development.

A major consideration of monitoring will be the type and source of potential pollutants to groundwater. Two general classes exist, point sources and nonpoint sources. Point sources may require fewer monitoring points than nonpoint sources.

Another important consideration is the degree of monitoring required. There are various levels of monitoring with various objectives. The extremes might be: 1) complete definition of the associated groundwater systems with many monitoring points which permit immediate recognition of induced changes over time, or 2) a few monitoring points addressed to the known existing groundwater systems which, at some uncertain time, might or might not record induced water quality changes. In this latter situation it would be difficult to assess the monitoring system effectiveness due to poor definition of the natural systems to be monitored.

Three basic zones must be considered for monitoring purposes:

1. Shallow, near surface aquifers and unsaturated zones (to establish influence of surface activities, airborne contaminants, etc).
2. Intermediate depth aquifers (to detect leaks in production and injection wells, and induced changes due to exploration drilling, etc.).
3. Geothermal reservoir aquifer systems (should injection or other activity suggest the need to have control data beyond production wells).

All of the above must be considered in terms of three-dimensional systems and the anticipated, or demonstrated, character of the pollutant source.

REPORT ORGANIZATION

Section 2 presents the conclusions reached as a result of this project.

Section 3 presents recommendations for future work on groundwater monitoring of geothermal energy development.

Section 4 provides an overview of geothermal energy systems, including reservoir types, exploration, development, and waste disposal systems.

Section 5 of the report discusses the legal and institutional framework for geothermal energy, as related to groundwater and groundwater monitoring. This overview covers Federal and state laws.

Section 6 is a summary of previously reported work on failure data analysis for geothermal development.

Section 7 presents a summary discussion of various groundwater monitoring techniques that may have applications in geothermal systems. It includes extensive tables detailing monitoring techniques, parameters measured, and applications.

Section 8 covers nondispersive contaminant transport modeling as applied to developing designs for groundwater monitoring networks for geothermal developments. It includes examples.

Section 9 provides a detailed discussion of geochemical reaction modeling with illustrative examples used throughout the section. Included are an appraisal of chemical parameters of concern, a discussion of geochemical reaction types and a discussion of geochemical modeling computer programs.

Section 10 of the report presents a summary discussion of the six-step monitoring methodology.

Section 11 provides three illustrative examples of the use of the monitoring methodology: the Raft River KGRA (Known Geothermal Resource Area) in Idaho, detection of leakage from a lagoon, and tracking and interception of contaminant plume.

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SECTION 2

SUMMARY AND CONCLUSIONS

Groundwater monitoring for the impacts from geothermal energy development, conversion and waste disposal is similar to groundwater monitoring for other purposes except that additional information is needed concerning the geothermal reservoir.

There are two basic types of geothermal reservoirs from which power production is now on line: vapor-dominated and liquid-dominated. The geothermal fluids are developed through production wells drilled into the reservoir. The fluid is used to turn turbines to generate the electricity and in most cases the spent fluid is returned to the geothermal reservoir through injection wells.

Geothermal effluent disposal is primarily regulated by EPA through the Safe Drinking Water Act. The requirements of the Underground Injection Control program under the Safe Drinking Water Act are more stringent than most state laws. With the exception of California, growth of the legislative and regulatory regime for geothermal development has been slow at the state level.

The failure data analysis has indicated that the highest probability of failure is associated with wells and that they should be the focal points for groundwater monitoring (Table 6.3). Additional years of operating experience utilizing currently developed technologies are needed to confidently estimate failure rates.

Monitoring has two different approaches: prevention and detection. Monitoring techniques fall into four categories: 1) monitoring the injection/production well, 2) monitoring in the saturated zone, 3) monitoring in the unsaturated zone, and 4) monitoring on or above the ground surface. The first three categories correspond roughly to the three major routes of possible interaction between geothermal waters and groundwaters.

POLLUTE is a groundwater computer flow model which can be applied to an anisotropic aquifer that is bounded by impermeable and/or equal potential boundaries. It is applicable to a wide range of groundwater contaminant problems. POLLUTE contains certain simplifying assumptions which must be taken into consideration. The user should be aware of these assumptions, apply the model to appropriate situations, and use the model with caution for situations that substantially deviate from the model assumptions. Since POLLUTE assumes that the contaminant is nondispersive, the arrival values that POLLUTE yields can be considered the 50 percent point along the contaminant's breakthrough curve. The location distribution coupled with the isochron distribution given by POLLUTE, enables the user to locate a contaminant plume at a given time. The well flow distribution enables the user to determine under a given scenario which well will be contaminated, how much contaminant will be intercepted, and how long it will take for the well to become contaminated.

There are, for any given geothermal system, five possible mechanisms by which leaked geothermal fluid chemistries might be altered. Four of these five mechanisms are related to solution/precipitation reactions resulting from 1) aqueous redox potential changes, 2) temperature changes, 3) pressure change effects on dissolved gases, and 4) exposure of fluids to new mineral assemblages. The fifth mechanism involves cation exchange reactions. Prediction of resultant fluid chemistries may be essential to unambiguous evaluation of geothermal impact at remote groundwater monitoring sites Potential chemical responses of geothermal water to system stresses can be modeled using equilibrium type chemical programs if the essential geothermal fluid data are known. If essential aqueous and mineral chemistry data are also available for an intruded, nonthermal aquifer, more sophisticated, mass transfer type chemical programs and modeling techniques can be used to predict changes in the geothermal fluid chemistry for monitoring purposes.

The six-step monitoring methodology used in this report is based on the one presented by Weiss, *et al*. (1979). It has been refined to include results of failure analysis and computer-based contaminant transport and geochemical models. The six steps are: 1) define baseline conditions, 2) analyze failure modes, 3) forecast aquifer conditions, 4) select monitoring sites and techniques, 5) design monitoring plans and alternatives, and 6) implement monitoring plan and modify as experience dictates.

Three illustrative examples have been presented to demonstrate the six-step methodology. The methodology was applied to the Raft River KGRA in Idaho and to hypothetical examples of leakage from a lagoon and contaminant plume tracking and interception. The results of these examples indicate that the key to groundwater monitoring is to continuously measure physical and chemical characteristics on the production and injection wells. For example, a change in annulus pressure may indicate leakage through the injection tubing. Changes in these characteristics should yield the first indication of a leak into a groundwater system. At most sites, the immediate groundwater systems are already naturally impacted by the geothermal fluid. This makes early detection of the geothermal fluid more difficult in monitoring wells. Monitoring wells can be used to assess the impact of a leak, that is to determine if there is a change in water quality.

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SECTION 3

RECOMMENDATIONS

CONTAMINANT TRANSPORT MODELS

Advective contaminant transport models (which ignore dispersion) are normally adequate for purposes of design of geothermal monitoring networks. POLLUTE, the model developed for this study, is specifically designed to be of maximum usefulness and minimum cost to run and interpret for monitoring network design. Use of an advective model, such as POLLUTE, eliminates the need for large amounts of hydrologic data and permits optimization of the geothermal monitoring network.

It would be useful to attempt to refine the model further to allow more accurate modeling of aquifer heterogeneity, leaky aquifers and contaminant adsorption. It is quite easy to make these modifications at the expense of computational complexity. However, it is not a trivial problem to develop a transform that will efficiently deal with aquifer heterogeneity and leaky aquifers.

It must be understood that the model will not predict exact arrival times of contaminants at discharge areas. The arrival times predicted by POLLUTE will be equivalent to the breakthrough of the 50% contaminant concentration. This is not seen as a great disadvantage since advective-dispersion models are probably inaccurate even when dispersivity values have been measured.

Since large contaminant leaks will often be detected prior to breakthrough in the monitoring wells, the field-measured contaminant arrival distributions can be used along with predicted arrival distributions from the model to help assess the extent of aquifer contamination.

GEOCHEMICAL MODELS

Computerized geochemical modeling methods are recommended for application to geothermal monitoring problems when used by experienced personnel on a site-specific basis. This work should include 1) selection and field supervision of essential baseline data collection directed to modeling needs, 2) determination of the degree of model sophistication required and selection of appropriate geochemical program types based on prior field data evaluation for the KGRA in question, and 3) interpretation of results, including selection of diagnostic remote monitoring parameters and identification of information gaps requiring further evaluation. Because adequate redox information was generally lacking in the analyses taken from the literature, more effort should be made to quantify this parameter in geothermal fluids. This effort should include redox evaluation and comparison between a number of direct and indirect methods. Redox information is important to studies involving corrosion of plant facilities as well as to impacts on nonthermal environments. It is very important to measure comparable data at all sites at a given KGRA for both thermal and nonthermal waters.

SECTION 4

GEOTHERMAL ENERGY SYSTEMS

INTRODUCTION

Development of geothermal resources for the generation of electricity was first successfully demonstrated at Lardarello, Italy in 1904. Current output from the vapor-dominated reservoir at Lardarello is 384 megawatt (MW). The first development of a liquid-dominated reservoir occurred in 1958 at Wairakei, New Zealand. Current output from Wairakei is approximately 140 MW. Development in the United States did not occur until 1960 when an 11 MW unit at the vapor-dominated reservoir at the Geysers in California was brought on-line. As of July, 1981, total world-wide output from geothermal sources was 2538 MW (Table 4.1).

A renewed interest in geothermal energy has occurred over the last 10 years as a result of increasing fossil fuel costs. Generating capacity in the U.S. is currently at 930 MW, of which 910 MW is generated from the Geysers. Output from sources throughout the western U.S. is expected to double over the next 5-10 years (EPRI, 1981). A major part of this increase will come from liquid-dominated reservoirs in the Imperial Valley of California (PIC, 1979). By the year 1990 total output from the Geysers is expected to be 2000 MW. Estimates of power generation in the U. S. for the year 2000 are as much as 16 gigawatt (GW) if current growth rates continue.

RESERVOIR TYPES

There are two basic types of geothermal reservoirs from which power production is currently on-line. These are vapor-dominated and liquid-dominated hydrothermal convection systems. Both systems are similar in that they require a heat source, groundwater, sufficient permeability to allow upward movement of heated fluids and production at a rate and depth which is economically exploitable. In both systems recharge to a deep aquifer system occurs at the margins of the systems. The deep aquifer is heated by contact with hot rocks, which in turn are heated by a

TABLE 4.1: CURRENTLY INSTALLED AND PREDICTED GEOTHERMAL CAPACITY FOR PRODUCING COUNTRIES PLUS THE NUMBER OF OPERATING UNITS (Dipippo, 1981)

Country	Current number of energy production units	Geothermal Capacity (MW) as of July 1981	Predicted Capacity (MW) for 1983
United States	18	932.2	1297.2
Phillipines	11	446.0	781.0
Italy	39	439.6	436.6
New Zealand	14	202.6	202.6
Mexico	5	180.0	425.0
Japan	7	168.0	223.0
El Salvador	3	95.0	95.0
Iceland	5	41.0	50.0
Kenya	1	15.0	30.0
USSR	1	11.0	21.0
Azores	1	3.0	3.0
Indonesia	2	2.2	32.2
China	7	2.0	8.0
Turkey	1	0.5	5.5
Totals	115	2538.1	3637.1

deeper heat source believed to be either molten or recently solidified magma. Liquid-dominated reservoirs occur more frequently than vapor-dominated reservoirs.

Vapor-Dominated Systems

Production from vapor-dominated systems is characterized by dry or superheated steam with little to no associated liquid and usually contain 5% or less noncondensible gases, other than steam. Vapor-dominated systems form when the amount of boiling in the deep aquifer is greater than the rate of recharge to the aquifer. As the saturated steam moves upward through the fracture system the decrease in pressure, the lowering of the boiling temperature and contact with hot dry rock forms dry or superheated steam. Only a small part of the steam discharges at the surface; the remaining steam condenses near the system margins and cycles back to the deeper aquifer system. Temperature variations within the vapor-dominated sections of the system are relatively small.

Surface manifestations of vapor-dominated systems include fumaroles, mud pots, mud volcanoes, turbid pools, and acid leached ground in active discharge areas. Springs associated with these areas characteristically have pH's as low as 2 to 3, contain high sulfates, but have chloride concentrations of 15 mg/l or less (White, 1973). Spring discharge in less active areas is typically slightly acidic to slightly alkaline bicarbonate sulfate and may be high in CO_2, B, or NH_4^+, but again are characteristically low in Cl^-.

Liquid-Dominated Systems

Production fluid from a liquid-dominated reservoir typically consists of a mixture of liquid and 10% to 30% steam. The steam forms as a result of decreasing pressure as the fluid moves up the well bore. To create the steam needed to drive a turbine, the fluid is passed through a device in which a rapid decrease in pressure occurs. This decrease in pressure allows the fluid to flash boil to steam, which is then delivered to the turbine.

Liquid-dominated reservoirs occur in a wide variety of rock types. Most commonly they are associated with fractured volcanic and granitic rocks, although one of the largest and hottest liquid-dominated reservoirs known occurs in sedimentary formations of the Imperial Valley, California. As fluids move upward through the system, cooling near the top of the reservoir permits precipitation of SiO_2, which tends to form a cap or self-seal of the geothermal reservoir. This sealing effect helps to retain heat in the reservoir but locally reduces the permeability in the upper parts of the reservoir. In the Imperial Valley area low permeability sediments and high salinity of the geothermal fluid prohibit upward migration.

The most common surface manifestation of liquid-dominated reservoirs is hot springs. Chemical variation between geothermal reservoirs can be quite significant, resulting in a wide range of spring chemistries. Chloride concentrations are usually greater than 150 mg/l, in liquid systems. The springs are characteristically high in SiO_2, Cl^-, B, Na^+, K^+, Li, Rb, Cs, and As relative to surrounding groundwater (White, 1973).

EXPLORATION

The purpose of any geothermal exploration project is to determine whether a particular resource area can be economically developed for the intended use. In the case of geothermal power production, the factors considered are whether the resource is of high enough temperature, has sufficient volume and permeability, whether the reservoir is vapor or liquid dominated and whether the production fluid has a chemical composition that does not prevent utilization for power production. A number of indirect techniques are initially used to determine these parameters, but the final determination can only be made through an exploration drilling program.

Initially, regional geologic and hydrologic studies are made. This work is used to delineate the extent of the thermally active area. Geologic mapping, including use of aerial photography, is used to determine the structural and lithologic boundaries of the area under investigation. Initial hydrologic investigations include sampling of both thermal and nonthermal waters to determine recharge sources and boundaries of the geothermal area.

A number of geochemical techniques are used to estimate the potential of a given resource area. Sampling of gases and water from hot springs can be used to determine the type of reservoir, estimate temperatures and quality at depth, and through the use of isotopic chemistry, determine the source of recharge. Concentrations of SiO_2 and relationships between Na-K-Ca have been successfully used to estimate reservoir temperatures, (Combs and Muffler, 1973).

The main purpose of geophysical techniques in geothermal exploration is for siting of the exploratory drill holes. Temperature or geothermal gradient surveys, heat flow measurements, electrical conductivity surveys and passive seismic methods have proven most useful. These techniques help to define the extent of the geothermal area and provide data on the temperature and chemical conditions at depth. Other geophysical techniques, such as active-seismic and gravity and magnetic surveys, are useful in defining regional geologic conditions, but generally do not provide data on the actual geothermal reservoir.

The final evaluation of a geothermal area is dependent upon the drilling of exploration holes. Final confirmation of the temperature, pressure, quality, and productivity acquired from these holes is used to evaluate the economic feasibility of further development of the geothermal reservoir.

DEVELOPMENT

Upon a positive evaluation from data acquired during exploration studies, initial planning and development of the reservoir is commenced. The first stage of development normally covers a period of years, during which production and injection well drilling and testing is completed. Wells are tested for periods of months, during which measurements of temperature, pressure, and chemistry of the fluids are determined. Generally, production wells which turn out to be poor producers are used for injection purposes.

Most geothermal areas are developed to their full potential in stages. Upon completion and positive results of the first generation unit, additional wells are drilled and generation facilities constructed.

During the period of testing, the data compiled are used in the selection and design of the power conversion system. In particular, the temperature and chemistry of the fluid are crucial to the selection of the conversion technique. A number of different technologies are currently available and several more are in the developmental stages. These methods can be divided into two basic groups, based on whether the fluid that drives the turbine is the actual geothermal steam or whether a secondary fluid heated by the geothermal fluid is used to drive the turbine.

The first method, known as the flash steam system, allows the geothermal fluid to flash to steam which is then delivered to the turbine. Two types of flash steam systems are currently in use, single and double flash systems. The difference between these types is that in the double flash system the unflashed fluid leaving the first flash tank is put through a second flash tank to produce additional steam. The steam from the second flash tank and the steam leaving the first turbine are combined to drive a second turbine. Most geothermal areas currently being developed that are considering a flash type system are planning to utilize the double flash technique.

The second basic type of energy conversion is the binary cycle system. In this design the geothermal fluid in an unflashed state is passed through a heat exchanger. In the heat exchanger, a secondary fluid such as freon or isobutane is heated to form a vapor which is used to drive the turbine. Binary cycle systems are used in areas such as Imperial Valley, California, where chemistries of the fluids are such that flashing creates unmanageable amounts of precipitation and scale formation.

DISPOSAL SYSTEMS

Current methods for disposal of geothermal fluids consist of either injecting the fluid back into the geothermal reservoir or surface disposal (Table 4.2). Injection of spent geothermal fluids is considerably more difficult and costly than surface disposal, but it minimizes the environmental impact on ground and surface waters, prolongs the production life of the geothermal reservoir, and prevents land subsidence. For these reasons injection studies have been conducted or are ongoing at most sites.

TABLE 4.2 DISPOSAL METHODS AT SELECTED EXISTING GEOTHERMAL SITES

Site	Percent Injected	Percent Surface Disposal
Larderello, Italy	20	80 to surface streams
Wairakei, New Zealand	0	100 to Waikato River
Otake, Japan	100	None
Hatchobaru, Japan	100	None
Cerro Prieto, Mexico	0	100 to evaporation ponds and Sea of Cortez
Ahauchapan, El Salvador	30	70 discharged thru 86 km long canal to ocean
Geysers, USA	100	None

Injection of fluid into a geothermal reservoir is done at depths either above or below the main reservoir to prevent cooling of the main reservoir. At the Geysers, injection is done at depths below the main reservoir and as far as possible from existing production wells. The wells used for injection are generally production wells which were poor producers. Injection of fluids at the Geysers has been very successful due largely to the low total dissolved solids of the fluid. Of the total steam produced at the Geysers, 20% is injected and the remainder is lost by evaporation in the cooling towers. Estimates of fluid injection at a liquid-dominated reservoir utilizing a flash type system are as high as 87% of the total fluid produced (Table 4.3). Injection tests with fluids of poor quality in Imperial Valley, California, have met with severe scaling and plugging problems. A potentially serious problem with injection systems is the mixing of fluids from a number of different production wells. The formation of precipitates can increase greatly when fluids with different chemical compositions and temperatures are mixed.

TABLE 4.3 ESTIMATES OF WASTE FROM SELECTED EXISTING GEOTHERMAL POWER PLANTS

Power Plant Location	1977 Output, MW	Reservoir Type(a)	Reservoir Temp, °C	Fluid Production Rates(b)				Total Dissolved Solids		Gas Wastes	
				Well Flow		Condensate(c)					
				T/MWh	T/yr x 10^6	T/MWh	T/yr x 10^6	ppm	T/yr x 10^3	% gas/steam wt	T/yr x 10^3
The Geysers, U.S.A.	520	DS	200	7.5	4.2	1.7	7.74	600(d)	4.65(d)	0.8	273
Larderello, Italy	420	DS	220	8.9	32.7	1.3	4.78	NA	NA	5	1640
Wairakei, New Zealand	193	FS	260	44.8	75.7	1.8	1.47	4,400(e)	333	2.2	333
Cerro Prieto, Mexico	75	FS	270	31.5	20.7	1.3	0.854	20,000(e)	414	1.2	49.7
Hatchoharu, Japan	50	FS	290	20	8.76	0.8	0.350	4.700(e)	41.2	0.3	5.26

(a) DS = dry steam; FS = flashed steam.
(b) Tonne/MWh = 1000 kg/MWh. Yearly rates of 8760 hr/yr assume continuous well flow.
(c) Condensate flow varies with weather conditions.
(d) TDS at The Geysers in condensate. Varies from 300 to 1000 ppm with weather conditions.
(e) TDS of wellhead fluids. At Cerro Prieto, fluids in the evaporator pond have about 75,000 TDS.

From Defferding, 1980.

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SECTION 5

LEGAL AND INSTITUTIONAL FRAMEWORK

INTRODUCTION

In many states with geothermal potential, the issues of geothermal effluent disposal and groundwater monitoring are not clearly addressed. Generally, legislation regarding geothermal production has been rather broad in most states and usually prescribes the general mandate that groundwater pollution is prohibited. Broad authority to promulgate regulations regarding geothermal production, effluent disposal, and groundwater monitoring is generally delegated to one or more state agencies. The objective of this section is to identify the current laws and regulations pertinent to groundwater and groundwater monitoring, and to identify the agencies primarily responsible for the administration of those laws and regulations.

FEDERAL LAWS AND REGULATIONS

Federal Water Pollution Control Act

The Federal Water Pollution Control Act (FWPCA) of 1972 as amended by the Clean Water Act of 1977 controls the disposal of wastes into surface waters (U.S. 92nd Congress, 1972 and U.S. 95th Congress, 1977). The goals of the FWPCA are to restore and maintain the chemical, physical, and biological quality of the nation's waters and to eliminate the discharge of pollutants into the nation's navigable waters by 1985.

Under the FWPCA, effluent discharges from geothermal plants would be considered point source discharges. Point source discharges are regulated through the enforcement of effluent limitations, written into individual discharge permits, and receiving water quality standards. The effluent limitations are designed on the basis of "best engineering judgment" and are established by either the U.S. EPA or by the states through an approved National Pollution Discharge Elimination System (NPDES) program.

Although the FWPCA does not specifically address geothermal effluent disposal, the EPA generally asserted jurisdiction over deep well injection through the FWPCA. The FWPCA further specified that in order for the EPA to approve a state NPDES program, the EPA must find adequate authority existing under state laws to control pollution into wells. The EPA's authority to require NPDES permits for injection wells, however, has been limited by the Federal courts to only those wells that may cause migration of contaminants to surface waters (Olpin, et al., 1978). Discharge permits under the NPDES program are issued for five years. Due to the effluent limitations imposed by the FWPCA, the only viable modes of disposal for geothermal effluents will be evaporation (subject to clean air provisions) and deep well injection.

Resources Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) of 1976 replaced the Solid Waste Disposal Act (U.S. 94th Congress, 1976). Under the RCRA, EPA was to define hazardous wastes and regulate the disposal, treatment, and storage of hazardous wastes for the protection of health and environment. EPA has recently provided that "drilling fluids, produced waters, and other wastes associated with the exploration, development, or production of crude oil, natural gases, or geothermal energy" are excluded from the definition of hazardous wastes and the provisions of the RCRA (U.S. EPA, 1981).

Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) is designed to provide health-based standards for drinking water and to protect underground sources of drinking water (U.S. 93rd Congress, 1974). The regulatory scheme is similiar to that of the FWPCA, and the legislative intent of the Act is to have the states develop and administer programs to protect "Underground Sources of Drinking Water" (USDW) from contamination by underground injection. Under the SDWA, the burden of proof is placed on the operator of an injection well to prove that injection well operations will not harm drinking water sources. Part C of the SDWA required EPA to develop minimum requirements for state "Underground Injection Control" (UIC) programs.

EPA first published regulations for UIC programs in 1976, but withdrew the regulations when confronted with widespread opposition. After considerable delay and public review, the EPA finally implemented the UIC program regulations on July 24, 1980. Under the regulations, the states had nine months (to April 24,

1981) to formulate UIC programs for EPA approval. An additional nine-month extension could be granted by EPA when state organizations needed to acquire the necessary authority from the state legislatures. If a state fails to institute an EPA approved UIC program, the EPA will retain the primary authority for regulating the provisions of the SDWA under a Federal UIC program. As with the NPDES program, some states will prefer to have EPA administer the UIC program rather than formulate their own programs.

The SDWA and EPA regulations prohibit any underground injection without a UIC permit or authorization by rule (an interim authorization pending permit approval). The proposed regulatory framework for the UIC program, the elements of an approved state UIC program, and the EPA procedures for issuing permits (when EPA administers a Federal UIC program) are specified in 40 CFR Parts 122, 123, and 124 respectively. 40 CFR Part 146 establishes the technical criteria and standards for state or EPA administered UIC programs. Various sections within Part 146 describe requirements for the construction, operation, monitoring, reporting, mechanical integrity, and abandonment of geothermal wells.

The EPA regulations designate 5 different classifications of injection wells. Geothermal injection wells are considered Class III wells (Section 146.05 (c)4). The classification scheme for injection wells is dependent on the relationship between the injection wells and sources of drinking water. EPA defines an USDW as any aquifer that "currently provides drinking water or contains less than 10,000 ppm TDS." Sections 146.01-146.10 of the regulations specify general provisions with respect to drinking water, classification of injections wells, use of the area review concept, corrective action, mechanical integrity, and the abandonment of wells. Sections 146.31-146.35 specify requirements and criteria for the director of the UIC program to apply in regulating construction, monitoring, and reporting of Class III wells.

The mandate of the SDWA is primarily a preventive one, and the main thrust of the act is to preclude further contamination to USDW rather than the restoration of aquifers already contaminated. The director or administrator of a UIC program, however, does have the authority to require the implementation of corrective measures when necessary to protect a USDW. Section 122.34 establishes a "no migration" standard for Class III wells, and provides that no UIC permit will be issued where any Class III well "causes or allows movement of fluid into underground sources of drinking water" (45 FR 33437). The regulation does not require total containment; it only requires that no contaminant reach an USDW. The rule further specifies that whenever injection or formation fluids are found to be migrating into an USDW, the director shall "prescribe such additional requirements for any construction, corrective action, operation, monitoring or reporting (including closure of the injection well) as necessary to prevent such movement."

UIC permits for Class III wells are issued for the life of the well. Plans for construction, operation, monitoring, and abandonment are written in as conditions of the permit. Any changes from the conditions of the permit require the approval of the UIC program director.

The construction regulations for Class III wells require sufficient casing and cementing be installed to prevent the migration of fluids into or between underground sources of drinking water and that such casing and cementing meet the designed life expectancy of the well (Section 146.32). Sound mechanical integrity must be shown initially for all new and existing Class III geothermal wells, and again every 5 years thereafter for the life of the well. To prove mechanical integrity (Section 146.8), the operator must prove 1) the absence of any leak in the casing, tubing, or packers, and 2) the absence of significant fluid movement into an USDW through vertical channels adjacent to the injection well bore. The absence of leaks is to be tested by monitoring annulus pressure or by pressure tests with fluids or gases. The absence of significant fluid movement is to be confirmed with temperature or noise logs.

The "area of review" for a Class III well is established by determining the Zone of Endangering Influence. The Zone of Endangering Influence is the area, the radius of which is the maximum lateral distance from the well in which pressures in the injection zone will cause migration of formation or injection fluids into underground sources of drinking water. The Zone of Endangering Influence is computed by a modified Theis equation (45 FR 4281). An alternate method of determining the area of review is to establish a fixed radius of not less than 1/4 mile, based on consideration of injection and formation fluid chemistries, hydrogeology of the area, and the history of groundwater usage by the surrounding populace. If there are any improperly abandoned wells in the area of review that might allow fluid migration into a USDW, the operator of an injection well may not operate his well at such pressures as to cause degradation of other aquifers until corrective action has been taken.

Monitoring requirements of Class III wells are established in Section 146.33 and are generally stated in terms of the objectives to be achieved. Various provisions concerning monitoring are listed below.

- Monitoring wells are to be completed into the injection zone. Fluid levels and parameters chosen to monitor water quality are to be measured weekly.

- Monitoring wells are to be completed into any overlying or nearby USDW. Quarterly monitoring is required to detect any migration of injection fluids into the USDW.
- Physical and chemical characteristics of the injection fluid are to be measured with sufficient frequency to yield representative data.
- Continuous monitoring devices are required to monitor injection pressures, flow rates, and volume.
- The results of all monitoring requirements are to be reported quarterly to the director of the UIC program.

Section 146.33 also prohibits certain operating practices. The operator may not operate at such injection pressures as will cause the initiation or propagation of any new or existing fractures in the injection or confining zone or cause the migration of injection or formation fluids into a USDW. In addition, no injection between the outermost casing protecting underground sources of drinking water and the well bore is permitted.

If a well does not inject into, through, or above a drinking water source, the director has the discretion to ease the requirements for monitoring, construction, area of review, mechanical integrity, and reporting of data (Section 122.43).

Under the UIC regulations the director of a UIC program may exempt certain aquifers which otherwise meet the definition of underground sources of drinking water (Section 146.04). An aquifer can be exempted if it does not currently serve as a USDW and it can or will not be used as a future source of drinking water because:

1) it is geothermal energy producing.
2) it is situated at great depth, rendering the recovery of drinking water economically impractical.
3) it is contaminated beyond practical economic recovery.

Consolidated Permit Regulations

In 1980, the EPA established the Consolidated Permits Program (40 CFR Parts 122, 123, 124, 125). The Consolidated Permits Program was designed to resolve the conflicting requirements and coordinate the regulations of the Hazardous Waste Management Program (under RCRA), the UIC program (under the SDWA), and the NPDES program (under the FWPCA). Section 40 CFR 123.72 now specifies that an approved UIC permit program satisfies the requirements for the regulation of disposal wells under the NPDES program.

Geothermal Steam Act

The Geothermal Steam Act (GSA) of 1970 created the guidelines under which the Secretary of the Interior may lease Federal lands for geothermal development (U.S. 91st Congress, 1970). The regulations adopted by the Bureau of Land Management (BLM) for the implementation of the Act are codified in 43 CFR group 3200. Under the Act, the geothermal supervisor (a designated representative of the Secretary of the Interior) may prescribe such rules, regulations, and permit conditions as necessary to carry out the provisions of the Act and to protect the environment (40 CFR 270.35). Such regulations may include the prevention of waste and the protection of water quality. The geothermal supervisor is subject to the supervision and direction of the Director of the U.S. Geological Survey (USGS).

The GSA requires that lessees must comply with all state and Federal water quality standards and pollution regulations as conditions of the lease. On Federal lands, the EPA is required to enforce state and Federal water quality and pollution regulations (Tarlock and Waller, 1977). The states may regulate deepwell injection by imposing stricter guidelines than those issued by EPA.

The GSA and the BLM regulations do not clearly address the issue of the applicability of state water laws on Federal lands. The regulations specify that "nothing in these regulations shall constitute an express or implied claim or denial on the Federal government as to its exemption from state water laws" (43 CFR 3242-2). The lack of clarity in the regulations has resulted in the contention by some state water agencies that the state water appropriation laws and state water well drilling regulations apply to drilling for geothermal resources on Federal lands (Olpin and Tarlock, 1978).

The application of state water laws as regards the appropriation of groundwaters may seriously hinder geothermal development in those states in which groundwater has already been overappropriated. A case may be made, however, that Federal water rights are implied to be reserved in the Act, and that Federal water rights are superior to state-based water rights arising subsequent to the Act. As geothermal developments have been a fairly recent phenomenon, no Federal lessee nor the Department of Interior has challenged any state's authority to apply state water laws.

Geothermal Resources Orders

The geothermal regulations listed in 30 CFR 270 describe generally the guidelines under which the geothermal supervisor shall prescribe Geothermal Resource Orders (GROs). As conditions may vary widely from one area to another, the GROs are designed for particular areas (Section 270.11). All aspects of geothermal production are subject to regulation and supervision by the supervisor. One of the purposes of the regulations is to protect the quality of surface and subsurface waters. The GROs generally contain the following provisions.

- Drilling is to be conducted in conformance with the terms of the lease and geothermal resource orders.
- Well spacing and well casing programs are to be approved by the supervisor and are to be designed to protect the environment, including groundwater quality.
- The lessee shall take all reasonable precautions to prevent 1) waste, 2) damage to any natural resource, 3) injury to persons, real or personal property, 4) any environmental pollution.
- Prior to commencing any operations on Federally leased lands, a plan of operation is required which, except for the exemptions listed in Section 270.34, shall include the methods for disposing of wastes and provisions for monitoring to insure compliance with all applicable regulations.
- A plan for production will contain baseline data concerning the existing air and water quality, covering a period of 1 year prior to the submission of the plan. (Section 270.34)
- No well may be drilled, redrilled, deepened, or otherwise altered without the approval of the supervisor.
- Well records and logs shall be maintained and shall include information on the content and character of mineral deposits and water in each formation, thermal gradients, temperatures, pressures, and analysis of geothermal waters. (Section 270.37)
- The proposed drilling and casing plan shall include information on the drilling methods used, the nature of the circulating media, the type of blowout prevention equipment and the proposed logging program. (Section 270.71)
- Monthly reports are to be submitted to the supervisor detailing the operation of the previous month and the results of any tests and environmental monitoring conducted. (Section 270.74)
- No well may be abandoned without the approval of an abandonment plan by the supervisor. The plan "shall provide for the preservation of fresh water aquifers" and for the prevention of saline or polluted water intrusion into such aquifers. (Section 270.45)

STATE LAWS AND REGULATIONS

The following states have laws and regulations pertinent to geothermal development and groundwater monitoring.

Arizona

Arizona's experience with geothermal development has been minimal. For regulatory purposes, geothermal resources are treated as mineral resources rather than water resources, and regulatory authority is exercised by the Oil and Gas Commission (OGC) under the Geothermal Resources statutes (Arizona Revised Statutes, 1981). The OGC is empowered to exercise supervision over the "drilling, operation, maintainance, and abandonment of geothermal resource wells as... to prevent damage to or contamination of any waters of the State and to prevent the discharge of any fluids harmful to the environment by reason of drilling, operation, maintenance or abandonment of geothermal resources". Although monitoring requirements for geothermal effluent disposal are not specifically mentioned in the statute, the OGC is empowered to make any regulations necessary to carry out the provisions of the statutes.

Geothermal waters are included within the statutory definition of geothermal resources, and have been exempted from State water laws (Arizona Revised Statutes, Section 27-667) except where geothermal waters are commingled with ground or surface waters, or the groundwater supply is impaired or damaged. Where a geothermal resource underlies a useable groundwater supply, the OGC requires proper casing and well construction to prevent any contamination of the groundwater. Section 27-652 of the Statutes provides "disposal of water or brines from a geothermal well, whether by ponding and evaporation, release to a water source... shall not damage or contaminate the underlying groundwater aquifer or pollute any stream, river or surface water." Further, the OGC may require reinjection of fluids where subsidence may occur.

The major piece of legislation controlling water pollution within the State is the "Arizona Water Pollution Control Law" (AWPCL). The AWPCL authorizes the Water Pollution Control Council (WPCC) to adopt water quality standards, effluent limitations, monitoring programs, and to adopt regulations to prevent, control, and abate pollution to all State waters (Arizona Revised Statutes, 1980). As geothermal development in Arizona has been primarily limited to exploration activities and as geothermal effluent disposal is not addressed in the AWPCL, it is impossible at this time to determine what impact any WPCC regulations will have on geothermal effluent disposal where geothermal waters commingle with surface and groundwaters.

California

In California, water rights consist of an amalgam of riparian and appropriation rights (Olpin et al., 1978). For percolating groundwaters the correlative rights rule has been adopted, and landowners are entitled to a proportionate withdrawal of percolating waters for reasonable use on the overlying land without securing appropriated rights. Any surplus of water in excess of the needs of the overlying land may be appropriated. The Department of Water Resources has jurisdiction over groundwater (U.S. Department of Energy, 1980).

The California statutory definition of geothermal resources (California Public Resources Code, Section 6903), does not specifically include water in the definition. The lack of a clear definition of geothermal resources with respect to geothermal waters may give rise to legal concerns as to whether the geothermal waters belong to the mineral estate or the surface estate and whether such waters must be appropriated. The geothermal resource is regarded as a part of the mineral estate.

The majority of the geothermal operations in the State have occurred at the Geysers, where the groundwater aquifers are physically separated from deep geothermal aquifers. In other areas particularly those containing liquid dominated geothermal systems, there will likely be closer relationships between groundwater and geothermal waters, giving rise to legal questions about water rights.

In California, geothermal operators may acquire a "Certificate of Primary Use" from the Geothermal Resources Board to operate a geothermal well on private, State, or Federal lands (California Public Resources Code, Section 3742.2). The Certificate of Primary Use provides a rebuttable presumption that the geothermal operator has ownership of the resource and such resources are not conflicting with existing groundwater uses. Any person who claims that their water rights are being affected by geothermal operations can protect those rights by rebutting the presumption. The burden of proof, however, is with the complaining party and the geothermal operator can not be enjoined to demonstrate noninterference until the presumption is overcome. This presumption does not bar nearby landowners from seeking injunctive relief from the courts upon contentions that their water is being polluted by geothermal operations.

California leads the world in the production and utilization of electricity produced from geothermal resources. Due to the extensive geothermal energy development and exploration undertaken in California, legislation and regulation governing geothermal resource utilization is more extensive than in any other state. The State Lands Commission (SLC), the Division of Oil and Gas (DOOG), the California State Water Resources Control Board and Regional Water Quality Control Boards, the State Solid Waste Management Board, and the Department of Health have regulatory responsibilities with respect to geothermal effluent disposal.

The Geothermal Resources Act provides the regulatory framework under which State public lands are leased from the SLC (California Public Resources Code, 1980). The SLC has the primary responsibility for geothermal resource development within the State. Section 6911 of the Act provides that the SLC may prescribe an exploration development program in the lease. Further, Section 6925.1 specifies that whenever the SLC determines that any operation under a geothermal prospecting or exploration permit or lease constitutes an unreasonable risk of pollution or contamination, the SLC shall order immediate suspension of any drilling and production operations except those that are of a protective, corrective, or mitigative nature.

Once the lease or permit is secured, the enforcement of sound engineering practices and the State-wide geothermal regulations are administered by the Geothermal Unit of the State Division of Oil and Gas within the Department of Conservation. The State-wide geothermal regulations are found in subchapter 4 of Chapter 4, Title 14, of the California Administrative Code.

According to Section 1914, a geothermal operator must obtain the approval of the State Oil and Gas Supervisor before any drilling, redrilling, or abandonment operations on any well begin or the conversion of an existing well into an injection well. Sections 1935, 1935.3, and 1935.4 are regulations requiring adequate casing, construction and blowout prevention equipment. The regulations are designed to protect or minimize damage to the environment or usable ground and surface waters. Sections 1937 and 1937.1 deal with those records and logs which are to be maintained by the operator or filed with the Division. These include drill logs, electric logs, water analysis reports and monthly production and injection records.

Sections 1954 and 1966 specify the tests and surveillance requirements necessary to insure proper casing, cementing, and construction integrity, and that the injected fluids are confined to the injection zone.

Before an injection well can be approved, the operator must furnish the Commission with an entire plan of operations, which includes information on reservoir conditions, the method of injection, the source and amounts of fluid to be injected, and analyses of the injection fluid and fluid from the receiving formation.

Water quality standards, water quality control programs, and regulations regarding effluent disposal to waters of the State (includes all surface and groundwaters) are administered and coordinated by the State Water Resources Control Board (WRCB) and nine regional water quality control boards as established through the California Porter-Cologne Water Quality Act (California Water Code, 1980). Through the Act the legislature declared regulation over the conservation, control, and utilization of the water resources of the State and that the quality of the waters of the State shall be protected. The Act authorized the WRCB to exercize all the powers delegated to the State under the FWPCA and any other Federal acts regarding water quality (Chapter 3, Article 4).

Within a region, the regional board is delegated the authority to coordinate water quality control (including prevention and abatement), and formulate and adopt water quality control plans for areas within the region (Chapter 4, Article 2). Any person discharging or proposing to discharge waste within any region that could affect the quality of the waters of the State is required to file with the regional board a report of the discharge containing such information as the board may require. Other provisions of the Act include:

1) The recognition that it may be possible to alter the quality of water to some degree without unreasonably affecting beneficial uses (Ch. 4, Art. 3, Section 13241).
2) Punitive measures for noncompliance with regulations and the WRCB authority to require corrective action when appropriate.
3) The delegation of authority to the WRCB to adopt regulations regarding water quality and the disposal of pollutants into wells pursuant to the FWPCA requirements and acts amendatory thereto (Chapter 5.5, Section 13382).
4) That the injection of wastes into any subterranean stratum that is used or is intended to be used as a domestic water supply is prohibited.
5) That the State Department of Health Services may also make and enforce regulations pertaining to underground injection of wastes.
6) Each county and city may adopt additional regulations, and restrictions with respect to waste disposal which might degrade waters of the State (Section 13002).

Surface disposal of waste is regulated by the WRCB, which has established statewide regulations for land disposal of wastes. The regulations cover waste disposal from ponds and lagoons, and from heat rejection systems (California Water Resouces

Control Board, 1976). Surface waste disposal permits are also required by the California Solid Waste Management Board and the State Department of Health.

The WRCB has established 4 different waste site classifications, which range from total prohibition of runoff to direct dumping into surface or groundwaters. In addition, the WRCB has classified wastes into three groups. Group 1 wastes are those wastes that contain toxic substances or substances that could affect the quality of usable waters. Article 3, Section 2520(B) identifies brines from geothermal plants as Group 1 wastes. As Group 1 wastes, geothermal effluent may only be disposed of in Class I or in rare instances Class II-1 sites. Class I sites require the complete isolation of wastes from waters, have stringent requirements for impermeable barriers, and cannot overlie usable groundwaters. No washout or overflow is allowed from the site. Class II-1 site requirements are less stringent than Class I, and require near isolation of wastes from waters, controls to minimize leachate production, and allow sites to overlie groundwaters with impermeable barriers.

In addition to the above laws and regulations, an environmental impact report is required by the California Environmental Quality Act (California Public Resources Code 21000 et seq). The requirement that an environmental impact report be prepared for any project that may have significant effects on the environment may have a direct impact on whether or not geothermal resources may be utilized.

Colorado

The Colorado Geothermal Resoures Act (GRA) defines geothermal steam, hot water, and brines as a part of geothermal resources (Colorado Revised Statutes, 1973a). Under the GRA, the Oil and Gas Conservation Commission (OGCC) has the regulatory control over the resource and issues geothermal leases and geothermal well permits. The resources are regulated as a mineral resource and correlative rights are recognized. The OGCC requires the operator of a proposed well to submit a resource development statement, which includes information detailing the measures to be used to protect against the contamination of surface and groundwaters. Specific conditions concerning the drilling, operation, maintenance, monitoring, and abandonment of geothermal wells may be written into the permit. Before a geothermal permit can be issued by the OGCC, the State Engineer (through an interagency application review procedure) must approve the geothermal well application. The State Engineer may also stipulate conditions to be written into the permit to ensure compliance with the State's water laws.

Groundwaters tributary to surface streams are integrated with the surface water appropriation system administered through the State Engineer (Colorado Revised Statutes, 1973b, c). Water rights conflicts are adjudicated through the courts, and the State Engineer enforces court decreed doctrine. In designated groundwater basins, an administrative permit is required from the Groundwater Commission as a prerequisite to a valid water right. Outside of a designated basin a permit from the State Engineer is required (Colorado Revised Statutes Section 37-90-173(3)(a)).

The geothermal regulatory scheme of the GRA is superimposed over the groundwater regulatory regime. Under the provisions of the GRA, geothermal producers are still subject to regulations generated by the State Engineer of the Groundwater Commission relating to the production or use of water from geothermal wells (Section 34-70-107(1-2)). Before a geothermal permit may be issued, the State Engineer must find that geothermal production will not impair existing groundwater rights. A geothermal producer must prove that the geothermal resource is isolated from groundwater sources or that unappropriated water exists.

The Colorado Water Quality Act (CWQA) is the primary piece of State legislation concerning water pollution (Colorado Revised Statutes, 1973d). The CWQA designated the Water Quality Control Commission (WQCC), within the Department of Health, as the regulatory agency responsible for establishing water quality standards, programs, effluent limitations, and the administration of the State NPDES program (Colorado WQCC, 1978).

Geothermal effluents are not specifically addressed within the WQCC regulations, but do fit within the broad definition of pollutants (Colorado WQCC, 1978). As such, geothermal discharges are subject to regulation under the State discharge permit guidelines. Specific monitoring requirements may be written into individual discharge permits as conditions of the permits.

The water quality standards established by the WQCC are designed to protect both surface and groundwaters. An anti-degradation policy has been instituted which provides "that no water quality degradation is allowed which would interfere or become injurious to existing uses" (Section 2.1.8). Some degradation may be allowed if the WQCC chooses to allow such degradation after considering all the pertinent economic and social concerns. Considering the State's anti-degradation water policy, the injection of geothermal fluids into the source formation will probably be the only allowable means of disposal.

Hawaii

The statutory definition of geothermal resources includes geothermal fluids (Hawaii Revised Statutes, Section 182-1(9)). Hawaii's geothermal resources are generally separated from fresh water lenses by the underground volcanic hydrology, and are almost exclusively located in the deeper salt water zones underlying the islands.

"Regulations on Leasing of Geothermal Resources and Drilling for Geothermal Resources in Hawaii" (Hawaii Board of Land and Natural Resources, 1978) have been established by the Hawaii Board of Land and Natural Resources. Under the drilling regulations, no well may be installed without a permit. In addition, the regulations address well spacing, bonding, well construction, casing, maintenance, abandonment, blowout prevention, injection, and the protection of fresh water lenses. The Department of Health administers the State NPDES program. The Hawaii Safe Drinking Water Act is closely modeled after the Federal SDWA and gives the Department of Health the authority to regulate all aspects of underground injection.

Idaho

In Idaho, the Department of Water Resources (DWR) issues permits for the appropriation of ground and surface waters (Idaho Code 42-203). The Director of DWR has the authority to designate critical groundwater areas. While not specifically addressed, geothermal fluids appear to fall within the statutory definition of groundwater: "all water under the surface of the ground whatever may be the geologic structures in which it is standing or moving" (Idaho Code 42-230(a) 1977).

The Geothermal Resources Act (GRA) of 1972 defines geothermal resources as 'sui generis', "being neither a mineral resource nor a water resource, but they are also found and hereby declared to be closely related to and possibly affecting and affected by water and mineral resources in many instances" (Idaho Code, 1972). In general, the GRA specifies that a permit to drill a geothermal production well is required in most instances from the DWR, the primary regulating agency for exploration and development of geothermal resources. The statutes provide for the exemption of specified geothermal activities such as greenhouses, space heating, hot water fish propagation and hot springs baths when such activities are supported by valid water rights permits. In addition, the operator must obtain a water appropriation permit if the well yields water for beneficial purposes other than heat energy or when geothermal operations will unreasonably decrease the groundwater available for beneficial uses by prior appropriators (Section 42-4005). When geothermal aquifers and groundwater aquifers are physically separated and there is no competition for the same geothermal waters for beneficial uses, no water appropriation permit is necessary.

Under the GRA and the Idaho 'Waste Disposal and Injection Well' Statutes (Idaho Code Sections 42-3901 to 42-3914), permits are required for the construction or alteration of wells to be used for injection purposes. In keeping with the GRA, the DWR has established minimum construction, abandonment, and monitoring requirements for geothermal wells (Idaho Department of Water Resources, 1975). The rules regarding injection well permits require the operator to furnish information regarding the method of injection, the nature, amount, and source of the injected fluid, a description of the receiving aquifer and fluids already within the injection zone. Section 42-3906 of the Injection Well Statutes requires the Director of the Department of Health and Welfare to make recommendations to DWR regarding approval or disapproval of the application.

Enforcement of water quality standards and regulation of effluent discharges into State waters are functions of the Department of Health and Welfare (DHW). The DHW has established 'Water Quality Standards and Wastewater Treatment Requirements' designed to protect the waters of the State for appropriate beneficial uses (Idaho Department of Health and Welfare, 1980). Beneficial uses of water include use for domestic and agricultural water supplies, recreation, wildlife, and aesthetics.

Waste water discharge to surface waters and into injection wells is allowed provided such disposal does not violate water quality standards or designated beneficial uses. Surface disposal is allowed if such waters are restricted to the premises of the disposal site and do not create a health hazard or nuisance. Groundwater monitoring requirements to insure compliance with the disposal regulations are specified on a case by case basis from the DHW (Section 1-2480).

Waste water discharges are also regulated by EPA under a Federal NPDES program. As Idaho does not have an approved NPDES program, the UIC program will probably be administered by the EPA.

Nevada

Geothermal development in Nevada has been primarily confined to space heating applications and exploration activities. The Geothermal Resources Statute (Nevada Revised Statutes, Chapter 534A) is the primary legislation concerning geothermal resource development and regulation. Section 534A.020 of the Nevada Statutes (of 1975) gives the State Engineer the authority to adopt regulations to insure the proper development of geothermal resources including "(C) establishing casing and safety device requirements, (D) establishing record keeping requirements, (E) establishing procedures to prevent pollution and waste, and (G) establishing well spacing requirements." Although the authority has been granted, no specific regulations concerning geothermal development have yet been adopted by the State Engineer.

The statutory definition of geothermal resources does not include the heat transport medium (geothermal fluids), and geothermal waters are considered as groundwaters and subject to appropriation through the State Engineer's office. The same procedure is used to appropriate surface and groundwaters. Geothermal wells are thus considered as water wells and must meet the minimum well standards listed in the 'Regulations for Drilling Water Wells' (Morros, 1981). The regulations (essentially unchanged since 1947) specify casing and abandonment requirements to prevent contamination and waste, and require that "every reasonable precaution be taken to prevent contamination of a potable aquifer". Specific requirements for drilling, construction, and abandonment of wells are written on a case by case basis into the permits for geothermal wells.

In "designated groundwater basins", no well may be drilled without first filing an application for the appropriation of waters, and obtaining approval from the State Engineer. In other basins, no permit is required to drill a well; however, an appropriation permit is required to produce the well.

The Division of Environmental Protection (DEP) regulates the disposal of wastes to surface and groundwaters, and administers the State NPDES program. Section 445.178(3) of the Nevada Water Pollution Control Law (Nevada Revised Statutes, Title 40, Chapter 445) allows the DEP to exclude water, gas, or other materials injected into a well or used to stimulate a reservoir of geothermal resources from the definition of pollutant if the DEP determines that no ground or surface water resource will be degraded. At the present time the DEP has no specific regulations concerning the injection of geothermal fluids. The DEP does have the general requirement, however, that no injection of waste waters contaminate surface or underground sources of drinking water (Nevada DEP, 1979). In cases where the DEP determines that there is a potential for contamination of surface or groundwaters, the DEP will require a discharge permit. The permits will be issued on a case by case basis and will contain such requirements for the construction, operation, abandonment, and monitoring of geothermal wells as the DEP deems necessary to control pollution. The State of Nevada has opted not to administer the UIC program (as mandated by SDWA), and the EPA is expected to be the primary regulatory agency governing geothermal effluent disposal.

New Mexico

Geothermal investigations have been undertaken at Fenton Hall and near Valley Caldera. The State Lands Office regulates the leasing of State lands for geothermal development pursuant to the "Rules and Regulations Relating to Geothermal Resources Leases" (1971).

The New Mexico Water Quality Act empowers the Water Quality Control Commission (WQCC) to adopt and enforce water quality standards, water quality programs, and regulations to prevent and abate pollution within waters of the State (New Mexico Statutes, 1977). Further, the Act requires the issuance of permits for the discharge of contaminants to waters of the State, both above and below the ground surface. The responsibility for the enforcement of the New Mexico Water Quality Regulations (NMWQR), adopted by the Commission, are delegated to other State agencies (New Mexico WQCC, 1967). Specifically, discharges from oil and gas operations affecting water quality are regulated by the Oil Conservation Commission (OCC). All other discharges to the waters of the State are regulated by the Environmental Improvement Agency (EIA). While not specifically addressed, presumably the regulation of geothermal effluent disposal would come under the authority of the EIA. Geothermal effluent disposal may also become regulated by the OCC if the Commission classifies geothermal energy as an energy source similar to oil and gas. The OCC currently regulates geothermal drilling operations through the "Rules and Regulation of Geothermal Resources" (Order No. R-4860, 1974). New Mexico does not have an EPA approved NPDES program, and thus, the EPA Regional Administrator regulates discharges under a Federal NPDES program as required by the FWPCA. The EPA will probably also administer the UIC program as mandated by the SDWA.

In addition to the Federal regulations, the New Mexico Water Quality Regulations provide for the regulation of discharges onto or below ground to protect those groundwaters of the State which have existing concentrations of less than 10,000 mg/l TDS for the present and potential future uses as domestic and agricultural water supplies. The water quality standards for groundwater with less 10,000 mg/l TDS are listed in Section 3-103 of the NMWQR, and provide that existing groundwater having a quality greater than the established standards may be degraded to the standards. Further, if the existing concentration of any water contaminant in groundwater exceeds the established standard, no additional contamination is allowed. Other provisions of the New Mexico Water Quality Regulations include:

- No person may allow effluent to discharge without an approved discharge plan (Section 3-104).

- Discharge plans shall provide for monitoring programs, contingency plans, and reporting requirements to insure compliance with the regulations during and after cessation of activities (Section 3-107).
- A discharger may petition for Commission approval of a discharge plan (Section 3-110) that does not meet the groundwater quality standards provided that the discharger can demonstrate:

  1) The maximum use of technology within the discharger's economic capability.
  2) That there is no reasonable relationship between the economic and social costs and the benefits (including attainment of standards) to be obtained.
  3) The plan will not create a hazard to publich health or undue risk to property.

The Water Quality Control Commission has established separate water quality regulations for discharges to surface streams. These regulations are found in the "New Mexico Water Quality Standards" (established 1973, revised 1980) and essentially express an anti-degradation policy.

In summary, the New Mexico water quality standards and regulations make distinctions between surface and ground waters. Groundwater may be degraded to the established standards while surface water degradation is only permitted when necessitated by economic and social concerns. Geothermal effluent disposal will likely be regulated by the EIA, the OCC, and the EPA.

Oregon

Oregon's experience with geothermal energy has primarily been direct heat applications such as space heating and ethanol production. Although Oregon has no geothermal electric power applications, the regulatory regime is more advanced than in most other states. Three regulatory agencies generally control geothermal development: the Department of Water Resources (DWR), the Department of Environmental Quality (DEQ), and the Department of Geology and Mineral Industries (DGMI).

The Oregon "Geothermal Resources" Act includes geothermal fluids within the statutory definition of geothermal resources (Oregon Revised Statutes, 1979). Fluids occurring at less than 250°F (bottom hole temperature) and less than 2000 feet in depth are excluded from the Act and are therefore treated as groundwater, subject to regulation by the DWR. The DWR administers the surface and groundwater permit systems and regulates the allocation of water. All groundwater rights subsequent to 1955 are appropriated. Under the groundwater classification, many of the geothermal wells used for direct heat applications are regulated as water wells. The DWR regulates the construction, operation, and abandonment of water wells in accordance with State policies governing water quality standards and water pollution

Geothermal fluids having bottom hole temperatures greater than 250°F or occurring at depths greater than 2000 feet are considered geothermal resources and are subject to regulation by the DGMI. The DGMI is the primary regulatory agency for geothermal development within the State. In 1972, the DGMI adopted "Geothermal Regulations" (Oregon Administrative Rules Compilation, (OAR), 1981). The Regulations control the drilling, construction, maintenance, operation, and abandonment of geothermal wells, encourage maximum economic recovery, and are designed to safeguard the life, health, property, and welfare of the people of the State.

Disposal by injection is the preferred method for handling geothermal effluents (OAR, Sections 632-20-154). In addition, Section 522.109 of the Oregon Statutes requires that "all geothermal fluids derived from geothermal resources shall be reinjected into the same reservoir at the discretion of the DGMI if they are in keeping with State water laws." The DGMI requires strict adherence to the injection well construction, operation, and monitoring requirements of the regulations. Section 632-20-159 of the regulations requires monitoring to insure that there is "no escape of geothermal fluids from the casings or through the annular space between casings and open holes except in the zone for which reinjection is permitted." Monitoring may include gauging pressure between casings, periodic testing for casing leaks, surveys to detect movement in adjacent rock formations, cement bond logs, temperature measurements, analysis of water chemistry, and the use of special wellhead equipment or other methods used in industry to monitor injection operations. The regulations also specify blowout prevention equipment and guidelines for all geothermal wells.

Oregon is extremely pollution conscious. The enforcement of Oregon's water pollution control laws (Oregon Revised Statutes, Chapter 468), regulations (O.A.R. Chapter 340), and water quality standards is done by the Department of Environmental Quality (DEQ). The DEQ is responsible for water quality management, the enforcement of waste treatment guidelines, and the administration of the Oregon NPDES program. The DEQ continues to retain jurisdiction over the injection of geothermal effluents. The disposal of geothermal effluents and the jurisdictional overlap of the DEQ and DGMI have not been a problem in Oregon due to the lack of major geothermal projects. Currently, the disposal or use of geothermal waters as groundwaters require permits from the DEQ and DWR.

Texas

Texas has experienced minimal geothermal development. The vast majority of Texas geothermal resources consist of geopressured resources along the Gulf Coast. Geopressured waters, along with hot water, steam, and brines are defined as a part of geothermal resources in the Geothermal Resources Act (GRA) of 1975 (Texas Statutes, S.B. 685).

The GRA provides that the Texas Railroad Commission (TRC) shall "regulate the exploration, development, and production of geothermal energy... and protect the environment against damage resulting from such exploration, development, and production." Section 26.131 of the Texas 'Water Quality Control' code (WQCC) provides that the TRC has the sole responsibility for the "control and disposition of waste and the abatement and prevention of pollution of surface and subsurface waters resulting from activities associated with exploration, development and production of oil or gas or geothermal resources..." (Texas Codes Annotated, 1981). Texas has an approved NPDES program, and the provisions of the program relating to pollution from oil, gas, or geothermal development are administered by the TRC. The Department of Water Resources (DWR) has jurisdiction over all other discharges and the general administration of the NPDES program.

The TRC has established statewide rules for oil, gas, and geothermal resources operations (Texas Railroad Commission, 1976). Various provisions of the rules are listed below:

* Geothermal exploration wells, production, and injection wells are to be operated such that no pollution to any stream, water course, or groundwaters will occur.
* The use of saltwater disposal pits without impermeable liners for storage and evaporation of geothermal water is prohibited.
* Geothermal water unfit for domestic, stock, or irrigation uses may be injected back into the following formations: all nonproducing zones of oil and gas or geothermal resources bearing formation waters unfit for domestic, stock, and irrigation purposes.

The Injection Well Act further requires the TRC to impose casing requirements taking into consideration the geology, hydrologic conditions, foreseeable future economic developments, and foreseeable future demands for the use of fresh water in the area (Texas Code Annotated, 1981b). The TRC may impose, through its permit process, any construction, abandonment, and monitoring requirements necessary to protect fresh water from pollution.

Generally, the only acceptable method of disposal of geopressured fluids will be by injection into saline aquifers. Surface water disposal is unlikely due to the Texas surface water anti-degradation policy and the high cost of waste water treatment (Texas Administrative Code, 1981).

Utah

The primary area of geothermal development in Utah has been in the Roosevelt Hot Springs area in the southwestern portion of the State.

The primary regulating agency for geothermal energy development within the State is the Division of Water Rights (DWR). The Geothermal Resource Conservation Act requires that geothermal wells be drilled, operated, maintained, and abandoned in such a manner as to safeguard the natural environment and public welfare and prevent waste (Utah Code, 1980). To achieve the above goals the DWR has established rules and regulations for geothermal exploration and production wells (Utah DWR, 1972). Proper casing and construction are required to prevent geothermal fluid migration between the geothermal reservoir and overlying strata, pollution to surface or groundwaters, and blowouts and premature cooling of the geothermal reservoir. To date, geothermal waters have been treated primarily as groundwaters subject to appropriation rights.

The primary piece of legislation regarding water pollution is the Utah Water Pollution Control Act (UWPCA) of 1981, which closely models the FWPCA and SDWA (Utah Health Code, 1981). The UWPCA is administered by the Water Pollution Control Committee (WPCC) within the Department of Health. The WPCC has the regulatory authority for the prevention, control, and abatement of pollution to the waters of the State, the establishment of water quality standards, effluent guidelines, rules governing underground injection, and the classification of waters according to beneficial uses. To insure compliance with the regulations, the WPCC may impose inspection, monitoring, record keeping, and reporting requirements on dischargers. In addition, the WPCC has been empowered to meet all requirements of the Federal water pollution control laws.

Prior to the formation of the Department of Health in 1981, water quality was managed by the Board of Health and the State Committee on Water Pollution within the Division of Health. The WPCC now administers the Utah Waste Disposal Regulations (Utah State Division of Health, Revised 1978, Parts 1 through 4) and exercises the authority that was previously vested in the Board of Health and the State Committee on Water Pollution. Many of the provisions of the UWPCA and the Wastewater Disposal Regulations are more restrictive than those of the FWPCA.

The disposal of geothermal effluents is not expressly addressed in the UWPCA or the Waste Water Disposal Regulations. The disposal of wastes to surface waters is prohibited as the policy of Utah on surface waters is essentially an anti-degradation policy. Waters with quality superior to the established standards are protected against degradation unless such degradation is justified as necesary by the WPCC for economic and social development. Other provisions of the UWPCA and Waste Water Disposal Regulations are listed below.

- No discharge of any waste to the waters of the State is allowed without a permit.
- Injection into fresh water aquifers is prohibited.
- Temporary surface ponding is permissible when proper engineering precautions have been used to prevent seepage from the ponds.
- Underground injection of waste is the only acceptable disposal method for large volumes of wastes. The wastes must be injected back into the production zone or any equally impure zone.
- In the event that the EPA does not approve the Utah water pollution control programs as related to the NPDES and UIC programs (i.e., the EPA has primary responsibility for the discharge permit system under the Federal NPDES and UIC programs), then no discharge permits shall be required under the UWPCA (Utah Code 26-11-20).

Wyoming

Geothermal resources developed in Wyoming has been minimal. Coal-fired electrical power plants are expected to meet Wyoming's growing electric power needs. Geothermal power development in Yellowstone National Park is prohibited. In addition, the State Engineer has the authority to "abolish, correct, discontinue or stop any condition which interferes with the natural flow of any thermal spring...located on State lands."

Due to the low level of geothermal resource development Wyoming's laws and regulations governing geothermal development, effluent disposal and groundwater monitoring have been rather general. Geothermal water and steam are included in the statutory definition of groundwater and, as such, are subject to appropriation through the State Engineer's office. The State water laws give the State Engineer broad supervisory powers over geothermal development in the State and the authority to require the abatement of any condition or the sealing of any well responsible for the admission of polluting material into underground waters (Wyoming Statutes, Section 41-3-901).

The State Board of Land Commissioners (SBLC) has established 'Rules and Regulations Governing the Issuance of Geothermal Resource Permits and Leases' (Wyoming State Board of Land Commissionrs, 1975). Various provisions of the rules haveing an imact on groundwater pollution are listed below:

- Geothermal operations are not to be carried on except in accordance with generally accepted good engineering practices. (Rule 11a.)
- Drilling operations may not be started on State lands until a permit or lease is obtained from the SBLC and such operations are authorized by the State Engineer. (Rule 11b.)
- The State Engineer may prescribe casing requirements and must approve any abandonment plan. (Rule 11C & 11L.)
- Geothermal wastes shall be discharged in accordance with requirements and prohibitions prescribed by the Water Control Board, within the Department of Environmental Quality (DEQ), which shall also approve the place and manner of such disposal.

Geothermal effluent disposal is not specifically addressed in the DEQ Rules and Regulations (Wyoming Department of Environmental Quality, 1974). The Wyoming Environmental Quality Act (Wyoming Statutes 35-11-101 to 35-11-302), however, does give the DEQ authority to require any point source (includes disposal wells) operator to install and maintain monitoring equipment, sample effluents and make reports. Wyoming's NPDES system is administered by the DEQ.

CONCLUSIONS

With the exception of California, geothermal development in most states has been slow, as have been the growth of the legislative and regulatory regime for geothermal development (See Table 5.1). Among the states, geothermal fluids are regulated as either mineral resources, water resources, or something between the two extremes. The legal definition of geothermal fluids is important, as in many states geothermal fluids are considered groundwaters and subject to state groundwater appropriation policies. Where groundwaters have been over-appropriated, or where geothermal energy production is considered to be a lower priority benefical use, compared to other designated beneficial uses, geothermal development will be slow.

In some jurisdictions, geothermal waters are excluded from the water rights regime and are considered as a part of the mineral estate. Conflicts of interest and jurisdictional overlap between regulatory agencies may arise when the geothermal resource is not adequately defined. Whereas mineral rights are the property of the mineral or surface estate, water rights are generally considered public domain subject to appropriation by the state.

Most of the states do not have specific regulations with respect to groundwater monitoring of injection well facilities. Rather, the authority to regulate monitoring of injection wells usually falls within the broad guidelines of the state water pollution control laws. Specific monitoring requirements are often written into individual permits on a case by case basis.

Geothermal effluent disposal will be primarily regulated by the EPA through the SDWA. The requirements of the UIC program are more stringent that most state laws. During the "new federalism" of the present administration, it is unlikely that many states will be willing to accept the responsibility of adminis-tering a more costly water pollution control program than is currently in existence.

TABLE 5.1 SUMMARY OF STATE AND FEDERAL LAWS CONCERNING GEOTHERMAL RESOURCES

	FEDERAL GOVERNMENT	ARIZONA	CALIFORNIA
GROUNDWATER LAW WATER RIGHTS REGIME	Applicability of state Appropriation Water Laws not addressed	Development minimal Reasonable use for percolating water	Riparian and correlative rights
GEOTHERMAL LAW	Geothermal Steam Act 30 USC 530 PL 91-581	Geothermal Resources Statutes, ARS title 27-601 to 675	Geothermal Resources Act PUB RES Code 6903
CLASSIFICATION OF RESOURCE, REGULATION OF GEOTHERMAL FLUIDS, REGULATORY REGIME	Water Resource 30 CFT 270.2 (g)	Mineral Resources Geothermal Fluids exempt from state water laws ARS 27-667	Mineral Resource PUB RES Code 6903
GEOTHERMAL REGULATIONS & REGULATORY AGENCIES	BLM-43 CFR Group 3200 USGS-GRO's, 30 CFR 270 USFS EPA SDWA	Oil & Gas Commission granted authority to regulate	Calif. Adm. Code Ch. 4, T. 14 D.O.G. State Lands Commission thru lease Conditions, County Regulations may apply
MINIMUM WELL STANDARDS &/OR AGENCY WHICH AUTHORITY IS DELEGATED TO. PERMITTING AGENCY	USGS-GRO's BLM-thru permit conditions EPA-regional administer of UIC	Well plan to be approved by Oil and Gas Commission	D.O.G. Calif.Adm.CodeCh4T.14
UNDERGROUND INJECTION CONTROL, APPLICABLE WATER POLLUTION CONTROL REGULATIONS AND AGENCIES WITH AUTHORITY TO CONTROL POLLUTION.	EPA-NPDES and UIC program Geothermal Supervisor GRO's	No specific regulations, water regulations don't apply	D.O.G. #4,WRCB Calif.Solid Waste Management Board, State Dept. of Health
MONITORING REQUIREMENTS, MONTHLY INJECTION REPORTS	Required in UIC program, Technical requirements 40 CFR 146	Oil & Gas Commission has authority to require monitoring	#4,5 by WRCB Geothermal Regs-DOG
INJECTION ALLOWED OR REQUIRED	w/appropriate permit from geothermal supervisor & UIC director	Oil & Gas Commission has authority to require re-injection	WRCB and Regional Boards Disposal Well permits
WELL PERMITS			D.O.G.

# - refers to reference citation

Abbreviations:
ARS - Arizona Revised Statutes
BLM - Bureau of Land Management
DOG - Division of Oil & Gas
GRO - Geothermal Resource orders
PUB RES CODE - Public Resources Code
USFS - U.S. Forest Service
WRCB - Water Resources Control Board

(continued)

TABLE 5.1 (continued)

	COLORADO	HAWAII	IDAHO
GROUNDWATER LAW WATER RIGHTS REGIME	Appropriation correlative rights apply to geothermal reservoir		Appropriation/permit DWR permit
GEOTHERMAL LAW	Geothermal Resources Act C R S T.34 A.70	HRS Section 182	Idaho Code 42-1001 Geothermal Resources Act
CLASSIFICATION OF RESOURCE, REGULATION OF GEOTHERMAL FLUIDS, REGULATORY REGIME	Mineral resource under OGCC subject to water law regulation	Water Resource HRS 182-1(9)	'Sui generis'
GEOTHERMAL REGULATIONS & REGULATORY AGENCIES	OGCC #6	Board of Natural Resources Regulations #12	DWR, Geothermal Regulations, #15
MINIMUM WELL STANDARDS &/OR AGENCY WHICH AUTHORITY IS DELEGATED TO. PERMITTING AGENCY	Well plan to be approved by OGCC & State Engineer	Dept of Health	#15, DWR waste disposal & injection wells ID code 42-3901 to 3914
UNDERGROUND INJECTION CONTROL, APPLICABLE WATER POLLUTION CONTROL REGULATIONS AND AGENCIES WITH AUTHORITY TO CONTROL POLLUTION.	*	Dept. of Health #12	Dept. of Health & Welfare, DHW, Water Quality Regs, #14
MONITORING REQUIREMENTS, MONTHLY INJECTION REPORTS	Monitoring provisions are to be written into the permit & leases, WQCC-NPDES program, *, #6	SDWA similar to Federal version regulated by Dept of Health	DHW-on case by case basis, monitoring written into permits & Rule 7 of DWR Geothermal Regs.
INJECTION ALLOWED OR REQUIRED	*, recommended. It is the only viable means of disposal	Injection into saline zones required	
WELL PERMITS			Permits thru State Dept. of Water Resources

# - refers to reference citation

* - No specific mention of geothermal disposal operations, authority may be inferred from the general wording of the legislation.

Abbreviations:

CRS - Colorado Revised Statutes
DHW - Dept. of Health & Welfare
DWR - Dept. of Water Resources
HRS - Hawaii Revised Statutes
ID - Idaho
OGCC - Oil and Gas Conservation Commission
WQCC - Water Quality Control Commission

(continued)

TABLE 5.1 (continued)

	NEVADA	NEW MEXICO	OREGON
GROUNDWATER LAW WATER RIGHTS REGIME	Appropriation NRS 534	Prior appropriation	appropriation/permit
GEOTHERMAL LAW	NRS 534.A		Geothermal Resources Act ORS ch 522
CLASSIFICATION OF RESOURCE, REGULATION OF GEOTHERMAL FLUIDS, REGULATORY REGIME	Water Resource	Mineral Resource N M Statutes 65-11-3	Mineral Resource Above 250°F at 2000' bottom hole temperature
GEOTHERMAL REGULATIONS & REGULATORY AGENCIES	Authority granted to State Engineer in NRS 534.A Water Well regs apply	States Lands Office thru G T Leases, Oil & Gas Commission thru G T regs.	DWR DGMI-Geothermal Regs #23 DEQ
MINIMUM WELL STANDARDS &/OR AGENCY WHICH AUTHORITY IS DELEGATED TO. PERMITTING AGENCY	To be approved by State Engineer Regulation for Drilling Water Wells	Oil & Gas Commission regulates for drilling GT wells	DGMI regulations
UNDERGROUND INJECTION CONTROL, APPLICABLE WATER POLLUTION CONTROL REGULATIONS AND AGENCIES WITH AUTHORITY TO CONTROL POLLUTION.	Authority granted to State Engineer, No specific regs at this time	WQCC-NM Water Quality Act & NM Water Qual. Regulations, Environmental Improvement Agency, Oil & Gas Commission	DEQ enforces water pollution control laws and regulations
MONITORING REQUIREMENTS, MONTHLY INJECTION REPORTS	* Nevada Water Pollution Control Law DEP	No NPDES or UIC program Oil & Gas Commission regulations.	DGMI-Geothermal Regulations #23 DEQ-NPDES Program
INJECTION ALLOWED OR REQUIRED	*	Limited groundwater degradation allowed.	Preferred method of disposal OAR 632-20-154
WELL PERMITS			DEQ & DWR at <250°F DWR & DGMI at >250°F

# - refers to reference citation

* - No specific mention of geothermal disposal operations, authority may be inferred from the general wording of the legislation.

Abbreviations:

DEQ - Dept. of Environmental Quality
DGMI - Dept. of Geology & Mineral Industries
DWR - Dept. of Water Resources
GT - Geothermal
NM - New Mexico
NRS - Nevada Revised Statutes
ORS - Oregon Revised Statutes
WQCC - Water Quality Control Commission

(continued)

TABLE 5.1 (continued)

	UTAH	WYOMING
GROUNDWATER LAW WATER RIGHTS REGIME	Appropriation w/ permit.	Appropriation
GEOTHERMAL LAW	Water Resource	Wyoming Stats 41-3-900's
CLASSIFICATION OF RESOURCE, REGULATION OF GEOTHERMAL FLUIDS, REGULATORY REGION	Water Resource	Water Resource
GEOTHERMAL REGULATIONS & REGULATORY AGENCIES	Utah Admin. Rules A 63-01-1 (1972) DWR	Dept. of Environmental Quality, State Engineer
MINIMUM WELL STANDARDS &/OR AGENCY WHICH AUTHORITY IS DELEGATED TO. PERMITTING AGENCY	DWR Regulations	Well plans to be approved by State Engineer
UNDERGROUND INJECTION CONTROL, APPLICABLE WATER POLLUTION CONTROL REGULATIONS AND AGENCIES WITH AUTHORITY TO CONTROL POLLUTION.	DWR-Geothermal Regs, WPCC-Utah Waste Disposal Regs, #38	*, Dept. of Environmental Quality to prescribe regulations
MONITORING REQUIREMENTS, MONTHLY INJECTION REPORTS	#38 *	To be approved by Dept. of Environmental Quality NPDES Regs - DEQ
INJECTION ALLOWED OR REQUIRED		
WELL PERMITS	DWR permit required	DEQ permit required, also permit from State Engineer

# - refers to reference citation

* - No specific mention of geothermal disposal operations, authority may be inferred from the general wording of the legislation.

Abbreviations:
WPCC - Water Pollution Control Committee
DEQ - Dept. of Environmental Quality
DWR - Dept. of Water Resources

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SECTION 6

FAILURE DATA ANALYSIS

INTRODUCTION

Failure data for all components of a geothermal development were compiled from a literature search and contact with individuals actively involved in geothermal development and regulation. Detailed discussions of the data and statistical analysis are contained in Miller and Zimmerman (1980 and 1982) and are summarized here.

Table 6.1 identifies the factors that contribute to failure of geothermal equipment. While failures may occur at any geothermal site by the mechanisms given in Table 6.1, the actual failure rate for a certain piece of equipment by a particular mechanism is site dependent. For example, in Imperial Valley, California, failures as a result of corrosion are expected to be relatively high because the geothermal fluid is very saline, but failures due to well casing cementing problems are reduced because drilling is done in sedimentary formations which rarely contain highly fractured or cavernous zones.

TABLE 6.2: GEOTHERMAL SYSTEMS FAILURE DATA SUMMARY

Failure Point	Number of Failures
Drilling Failure	3
Production Well	28
Production Wellhead	3
Surface Piping	49
Injection Wellhead	1
Injection Well	None Reported

Table 6.2 summarizes the record of failures compiled during this study. Some of the failures were due to lack of operating experience and inadequate materials. Technological advance in

TABLE 6.1: CAUSES OF GEOTHERMAL EQUIPMENT FAILURE

Initial Condition	Resulting Failure Mechanism	Possible Failure Point
High Temperature	1) thermally induced stress	All components
	2) thermal cycling	Well casing problems most severe
Poor Quality Fluids	1) corrosion	All components
	2) scale	"
	3) abrasion	"
	4) dissolved gases	"
Geologic Environment	1) drilling and cementing problems associated with lost circulation zones	Well casing
High Pressure	1) pressure induced stress	All components
Present Stage of Development	1) inadequate materials	All components
	2) inadequate design and workmanship	"
	3) lack of operating experience	"
Natural Disasters or Accidents	1) landslides	All components
	2) earthquakes	"
	3) accidents as a result of personnel error	"
	4) vandalism or terrorism	"

recent years should eliminate some of the failures experienced in the past. In general, detailed data on individual failures were not available. This lack is explained, in part, by the difficulty in establishing actual cause of failure. It is particularly difficult to determine causes of well failure since failures can occur hundreds or thousands of meters below ground level. Well failures pose the greatest potential environmental impact because the difficulties in detecting and repairing casing failures make possible large quantities and durations of uncontrolled discharge.

The failure data collected and failure rates derived from nuclear power plant components were utilized in a preliminary statistical analysis.

FAILURE ANALYSIS

To demonstrate this analysis, the hypothetical energy conversion system will be placed on the Roosevelt Hot Springs Known Geothermal Resource Area (KGRA), near Milford, Utah. This is a liquid-dominated system with a depth to the top of the reservoir of 820 m. It is assumed that wells drilled in this development will average 900 m in depth. The principal groundwater reservoir in the Milford area is the unconsolidated valley fill alluvium. Well logs show that this material is between 60 and 150 m thick in the KGRA and it is assumed that each well passes through a vertically unconfined aquifer, A_1, 110 m in thickness. Logging of well DH 14-2 revealed a cold water entry zone, between 200 and 230 m, which will be treated as if it were a confined aquifer, A_2, of potential importance as a source of domestic or agricultural water.

For conceptual convenience assume that distribution of location of well casing failure is independent of depth. Further assume that an aquifer is only contaminated if the failure occurs within the aquifer. Therefore, if there is a casing failure in the zone of aquifer A_2, the probability (p) of contaminating aquifer A_2 is 1. If the failure occurs anywhere else the probability of contaminating aquifer A_2 is zero. The probability of contaminating aquifer A_2, given that the well has failed, is the ratio of the thickness of the aquifer to the depth of the well, 30/900, or 0.03. Likewise the probability of contaminating aquifer A_1, given a failure in the well is, 110/900, or 0.12. The probability of not contaminating aquifer A_2 by one or more of the 28 production wells in a given calender year is p^{28}, where 1-p is the product of the probability that A_2 will be contaminated given a failure (0.03) and the probability that a 900 m well will fail in a year. Data from the Wairakei field indicate that the probability of a 900 m production well failing in a calendar year is about 0.014. Therefore, the probability that a given well will fail in a calendar year and that it will contaminate aquifer A_2 is 0.00042. The probability of one or more production well failures in a calendar year which contaminate aquifer A_2 is $1-0.99958^{28}$ or 0.01. This analysis is tentat and further work is required to refine the estimated probability of failure of a well. By identical logic, the probability of failure in a calendar year of at least one injection well which impacts aquifer A_2 is 0.006.

Using the reasoning above, the probability of contaminating aquifer A_1 during a calendar year by production well failure is estimated to be 0.05 and the probability of contaminating A_1 by failure of an injection well is estimated to be 0.02. Injection of geothermal fluid is not done at Wairakei and probabilities computed above assume the same life expectancy for injection well as for production wells.

Probabilities of failure of aboveground components were estimated by Sung, et al., (1980) from data compiled in the Reactor Safety Study of 1975 (also known as WASH-1400 or the Rasmussen Report). They estimated that the probability of a major wellhead rupture in this geothermal energy conversion design during the 40-year design life is 0.008. Further, they say "Minor leaks are to be expected. Each gasket in the system would be expected to fail at least once during the assumed 40-year design life." If we assume that the probability of a major wellhead failure is constant over time, then the probability of a particular wellhead failing in a given calendar year is estimated to be 0.000005, the probability of there being at least one production wellhead failure in a calendar year is estimated to be 0.0001 and the probability of at least one injection wellhead failure in a calendar year is estimated to be 0.00007.

If the probability of failure of piping is 1×10^{-10}/hr/300m (Sung, et al., 1980) then the probability of at least one failure in 12,200 m of production piping in a calendar year is 0.00004 while the probability of at least one failure in 8,800 m of injection piping during a calendar year is 0.00003. These numbers are applicable to piping in a nuclear reactor, built to more stringent specifications than geothermal piping, and the estimated probabilities of failure may be too low. On the other hand, the stresses may not be as severe.

The probability of a major failure of the conversion system during its 40-year design life is estimated by Sung, et al., to be 0.001. Making the assumption that these failures are distributed uniformly over the 40-year lifetime, the probability of failure in a calendar year is estimated to be 0.0003.

The probabilities of failure in a calendar year of the various components of the geothermal energy conversion system are summarized in Table 6.3. The estimates of probabilities in this table are primarily useful in a relative sense, to indicate parts of the system which are more likely or less likely to fail, rather than as absolute numbers.

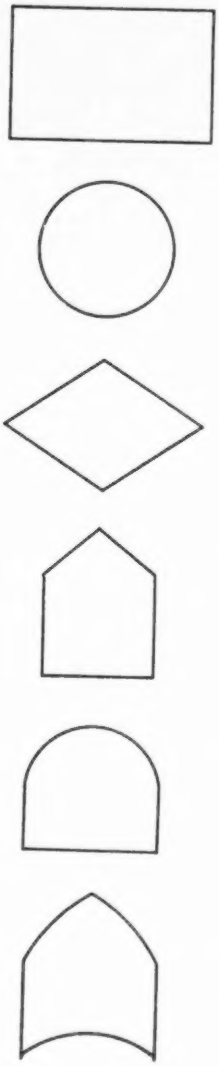
TABLE 6.3: RELATIVE ANNUAL PROBABILITIES OF FAILURE OF MAJOR COMPONENTS OF A HYPOTHETICAL DOUBLE FLASH GEOTHERMAL CONVERSION SYSTEM AT ROOSEVELT HOT SPRINGS KGRA

Probability (p)	Cause
0.01	Production well failure contaminating aquifer A_2
0.05	Production well failure contaminating aquifer A_1
0.0001	Production wellhead failure (major)
0.00004	Production piping failure (major)
0.00003	Failure in conversion system (major)
0.00003	Injection piping failure (major)
0.00007	Injection wellhead failure (major)
0.02	Injection well failure contaminating aquifer A_1
0.006	Injection well failure contaminating aquifer A_2

FAULT-TREE ANALYSIS

Fault-tree methodology was also applied to the data collected (Barlow, et al., 1975). This technique is a method of systems safety analysis which was developed in the early 1960's in the aerospace industry. The purpose of applying fault-tree methodology to a geothermal energy development is to identify the possible failure modes which would result in release of geothermal fluid and the possible sites of failure. The first step in a fault-tree analysis is the formulation of a fault tree figure, which graphically depicts the failure of system elements leading to an undesired event. Starting at the bottom of the figure a sequence of events are defined which, if satisfied, lead to the top or undesired event. If sufficient data exist, the probability of failure of each event can be determined. Even when these data are not available, as was found for geothermal energy systems, the fault-tree figure is still useful. It identifies the mechanisms and events that lead to failure, which in turn is one consideration in the selection and placement of monitoring equipment.

Figure 6.1 shows the standard symbols and definitions used in fault tree figures. The fault tree analyses shown in Figures 6.2 and 6.3 have been developed on a generalized basis. Figure 6.2, which defines the events leading to the failure of well casing, is applicable to both production and injection wells, but the probabilities of failure of the events shown will differ between the two types of wells. The same is true for Figure 6.3.



- Fault Event - The output of a logic gate which is dependent on the type of logic gate and the inputs to the logic gates.

- Primary Fault Event - A basic inherent failure of the system element being considered.

- Secondary Fault Event - A failure which is the result of excessive environmental or operational stress.

- Switch Event - Represents a state of system which is expected to occur or to never occur.

- Logic Gate (and) - all inputs to the "and" logic gate must be met to produce the output of the gate.

- Logic Gate (or) - any input to the "or" logic gate will produce the output of the gate.

Figure 6.1: Standard fault-tree symbols

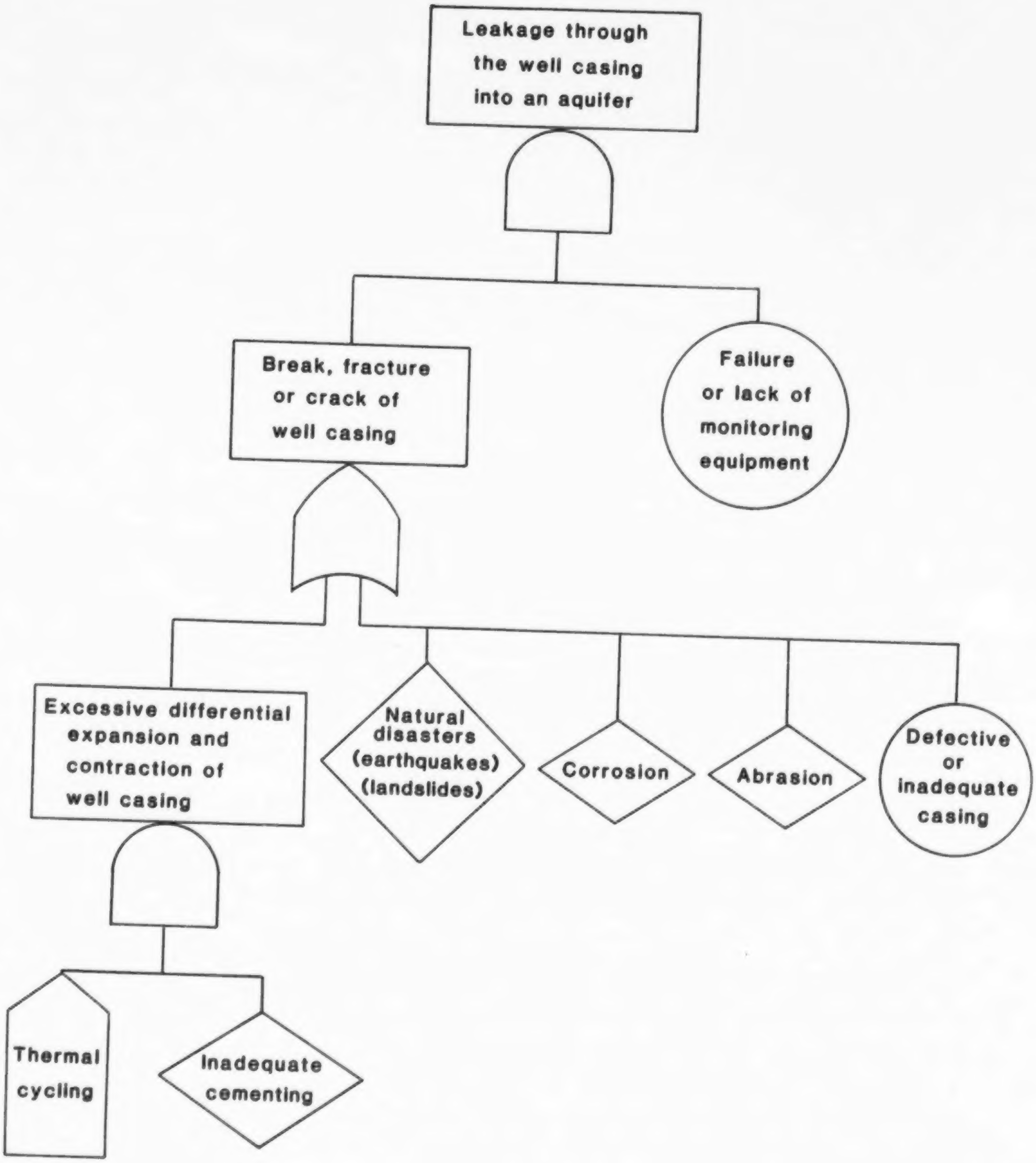

Leakage through the well casing into an aquifer
Break, fracture or crack of well casing
Failure or lack of monitoring equipment
Excessive differential expansion and contraction of well casing
Natural disasters (earthquakes) (landslides)
Corrosion
Abrasion
Defective or inadequate casing
Thermal cycling
Inadequate cementing

Figure 6.2: Fault-tree diagram for release of geothermal fluid from a well casing failure

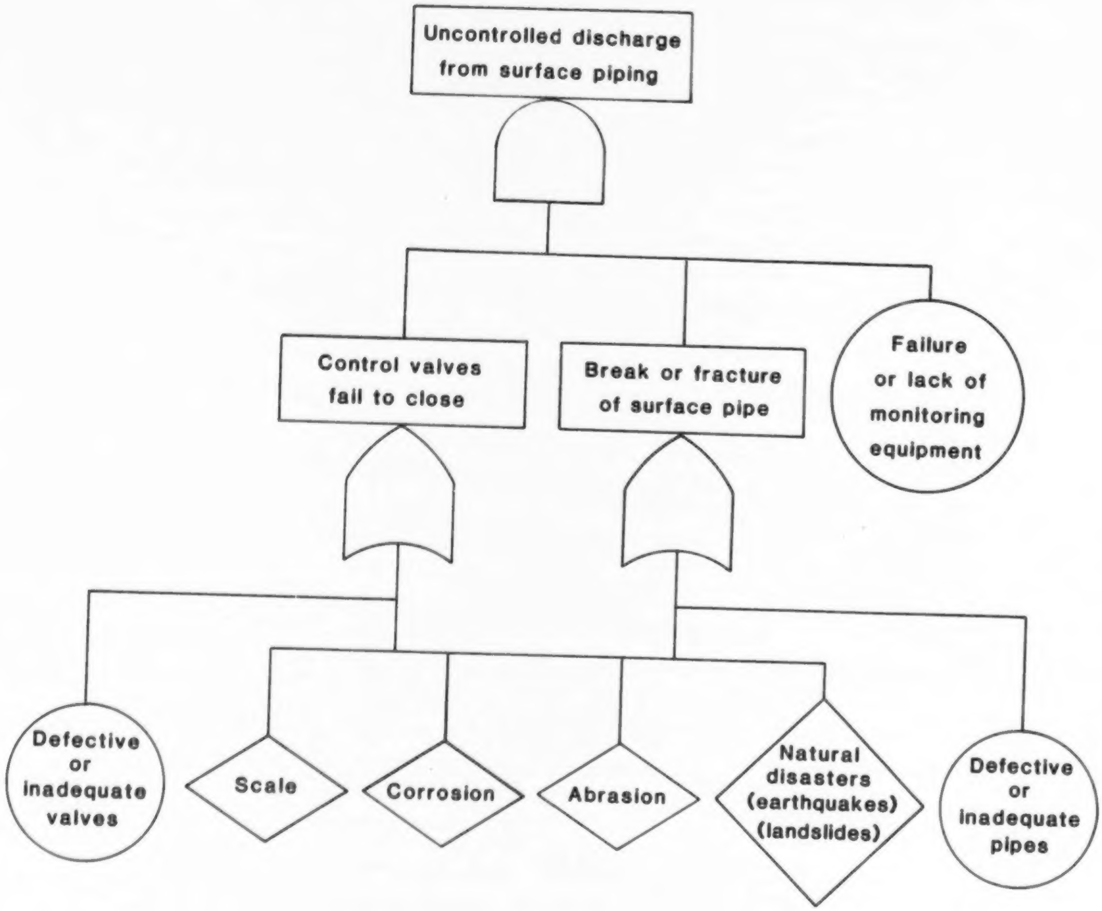

Uncontrolled discharge from surface piping
Control valves fail to close
Break or fracture of surface pipe
Failure or lack of monitoring equipment
Defective or inadequate valves
Scale
Corrosion
Abrasion
Natural disasters (earthquakes) (landslides)
Defective or inadequate pipes

Figure 6.3: Fault-tree diagram for the release of geothermal fluid from failure of a surface pipe

The mechanisms of failure are similar for production and injection piping but the probabilities of failure are not expected to be the same.

Each geothermal site should be evaluated on an individual basis and a corresponding fault tree figure constructed. This requires a detailed site plan that includes the types of materials used and a complete understanding of the operations and conditions at the site.

FAILURE DATA SUMMARY

While it is important to acquire more failure data, including data on failures of the same types of equipment in similar environments, it is unlikely that this will lead to satisfactory precision of estimates of failure rates soon because conversion of heat from geothermal fluids to electricity is a relatively recent activity. Thus, determination of reasonable coefficients of variation for the small probabilities of failure estimated in Table 6.3 is unlikely until considerable additional operating experience has been acquired. Table 6.3 does demonstrate in a relative sense that the highest probability of failure is associated with wells. Since well failures are difficult to detect, can involve large volumes of fluid, and can directly impact groundwater resources, focal points for groundwater monitoring should be directed towards both production and injection wells.

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SECTION 7

GEOTHERMAL MONITORING TECHNIQUES

INTRODUCTION

The chemical and physical nature of geothermal fluids may constitute an environmental hazard to groundwater quality in areas of geothermal development. For this reason, the prevention or detection of groundwater contamination is necessary and can be greatly facilitated by various monitoring techniques. This section does not attempt to integrate those techniques into a complete monitoring program, but rather defines various monitoring methodologies that may have applications in geothermal systems.

MONITORING TECHNIQUES

Tables 7.1 - 7.4 constitute the bulk of this section, and are concerned with individual monitoring techniques. The tables were compiled from the existing literature and are broken down into four categories: 1) monitoring the injection/production well, 2) monitoring in the saturated zone, 3) monitoring in the unsaturated zone, and 4) monitoring on or above the surface. The first three categories correspond roughly to the three major routes of possible interaction between geothermal waters and groundwaters. These contamination routes are: 1) movement of geothermal fluids through the production or injection well casing, 2) hydraulic interaction between groundwater and geothermal fluids through unknown pathways, such as fractures or abandoned wells, and 3) downward percolation from evaporation ponds, surface spills, etc.

When considering specific monitoring techniques, it should be recognized that there are two basic approaches to monitoring. One is monitoring the physical condition of such things as the integrity of the injection or production well to insure that failure does not occur. This sort of monitoring is preventive in nature. The second type of monitoring will actually try to detect contamination that has occurred. Both of these techniques

TABLE 7.1: MONITORING THE INJECTION/PRODUCTION WELL

Monitoring Technique	Parameters Measured	Applications	Comments	References
Volume of fluid injected	Volume	Allows estimates of wastewater travel and interpretation of pressure data.	Required by regulatory agencies and is continuously monitored.	15,53,56
Well head injection pressure	Pressure	Gives a record of reservoir injectivity. Pressure must be kept below values that cause either damage to well facilities or cause hydrofracturing of the reservoir or confining formation.ing formation.	Required by regulatory agencies and is continuously monitored. If hydrofracturing occurs contamination of ground water may occur.	15,53,56
Annulus pressure	Pressure	Changes in pressure may indicate leakage thru the injection tubing, tubing-casing or the packer.	Continuously monitored.	15,53
Chemical analysis of injected fluid	Fluid chemistry	Gives a record of chemistry of the fluid. Complete chemical analysis may be done on a periodic basis with more frequent analysis of troublesome species such as Cl^-, H^+ and H_2S that cause corrosion or of elements such as As, Bo and Hg that are of environmental concern.	Sample procurred before injection. Which species are measured and the frequency of measurement will probably depend on the locality.	15,53,56
Suspended solids in fluid	Suspended solids	May help evaluate problems due to reservoir clogging.	Sample procurred before injection and is measured periodically.	15,53,56
Sulfide specific ion probe	Sulfide Activity	Allows inline measurement of sulfide activity. Monitored due to its corrosive nature on the well.	Can give a continuous record. The probe was being developed for geothermal conditions, but the status of its development is unknown.	9,53
Corrosion coupons	Corrosivity of fluid	Strips of the well material may be inserted into the injection well and removed periodically for corrosion inspection.	This technique would allow estimates of the corrosion rate of the well materials and maintenance needs may be determined.	19,53
Pulling of tubing and visual or instrumental inspection	Condition of well casing	A method to determine the integrity of the casing.	Although this allows inspection of the well it may require long shut-down periods.	15,53
Insitu pressure testing of the injection well casing	Condition of well casing	May be performed periodically in operating wells by setting temporary plugs or packers. The well is subjected to a specified amount of fluid pressure. A rapid decline indicates leakage from the casing.	This may be done periodically in operating well, and may not require long shut-down periods.	15,53,56
Down hole Geophysics				
Acoustic borehole televiewer	Takes oriented acoustic "Photographs" of borehole well in the form of a continuous log.	Can be used in cased holes as an inspection tool to map cavitation pitting, perforation plugging or enlargement or casing breaches. It is also used for mapping of fracture zones, bedding planes vugs etc.	This instrument is being developed for geothermal use. Some problems remain with the acoustic sensor but should be remedied. It must be used in a fluid-filled hole.	56,57,58
Cement bond log	Records P-wave attenuation	Used to determine the integrity of the cement in the well. Can detect channeling behind the casing.	This instrument is being developed for geothermal use. The status of development is unknown. This instrument is for use in fluid-filled holes.	38,50,56
Conductivity probe	Conductance of fluid, this gives a measure of TDS.	Allows inline measurement of conductance. This gives an indication of fluid chemistry.	Can give a continuous record. The probe is developed for geothermal conditions.	9,53
Eh-probe	Eh-of fluid	Allows inline measurement of Eh. This gives an indication of the corrosive potential of the fluid.	Can give a continuous record. The probe was being developed for geothermal conditions. The status of its development is unknown.	9,56
pH-probe	Hydrogen ion activity	Allows inline measurement of pH. Monitor due to the dependence of scaling and corrosion of well components on the fluid pH.	Can give a continuous record. The probe was being developed for geothermal conditions. The status of its development is unknown.	9,15,53,56
Temperature probe	Temperature of injected fluid.	Allows inline measurement of temperature. Gives a record of the temperature of the injected fluid needed for reservoir management.	Allows continuous monitoring of fluid temperature in the well or at the well head.	7,9,15,20, 25,26,40, 52,53,56
Annulus fluid conditions	Complete chemical analysis, specific species analysis, temperature pH, Eh, conductance	Tapping the annulus fluid allows periodic measurements. The inline techniques discussed above may apply. Changes with time of the measured parameters may indicate leakage thru the injection tubing, tubing-casing or the packer.	These parameters may be continuously monitored or periodically depending on needs.	15,53,56

TABLE 7.1: MONITORING THE INJECTION/PRODUCTION WELL (continued)

Monitoring Technique	Parameters Measured	Applications	Comments	References
Amplitude sonic log	Records compressional and shear wave amplitudes	Used to indicate cement bond quality. It is also used for fracture mapping, pore geometry determination and lithology characterization.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56
Caliper log	Produces a profile of casing size variations	This can be used to determine corrosion or scaling in the casing.	Prototype geothermal tool has been developed. It has a 0.1 in accuracy.	50,56
Temperature log	Records temperature in the well bore as a function of depth.	Important use in monitoring is locating zones of fluid entry or discharge in the borehole and detection of fluid flow behind pipe & casing. It is also used for correction factors for other log interpretations.	Various tools have been constructed and field testing in geothermal systems.	1,3,7,14, 20,25,26, 40,50,56
Flow meter log	Records fluid velocity versus depth.	Indicates changes in flow patterns and is also used to detect inflow or outflow from within the well. Therefore, leakage can be determined.	Various tools have been constructed and tested in geothermal systems.	7,20,41, 50,56
Fluid pressure log	Measures fluid pressure as a function of depth	Used for well control and determination of fluid movement. This can be used to monitor injection pressure (See page 1 of table).	Various tools have been constructed and tested in geothermal systems.	1,7,12,14 20,25,26, 32,40,50,56
Gravity meter log	Measures the gravitational acceleration at points in the well.	Can give an indication of formation plugging due to injection. Porosity, density and average bulk density can also be determined for the formation materials.	A high temperature and pressure prototype has been developed for use in geothermal wells.	56,22
Radioactive/ chemical tracer technique	Records the level of an introduced tracer.	Determine fluid velocity or detect flow behind the casing by use of a probe or detector.	Prototypes have been developed for geothermal systems.	3,38,56
Fluid sampler	Collects borehole fluid	For determining borehole water quality. May indicate reactions taking place with the well casing.	Various tools have been constructed and field tested in geothermal systems.	3,33,47,50
Gamma spectrometry log	Records natural distribution of gamma radiation.	Identification of artificial radioisotopes in fluid could be used as a detector in radioactive tracer tests.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56
Gamma-gamma density log	Records the intensity of gamma radiation from a source in the probe after it has backscattered and attenuated within the borehole and surrounding rocks.	Determines cavities behind the well casing and could be used to insure well is correctly completed. Also used to locate casing collars and the position of cement behind the casing. Records significant density changes in the fluid.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56
Neutron log	Counts number of neutrons present at different energy levels or the number of gammaphotons produced by neutron reactions.	Can be used to determine hydrogen chlorine or silicon density. This may point to applications for corrosion/scaling monitoring.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56
Pulsed neutron log	Measures thermal neutron decay time	Can measure chlorine density or detect channeling behind the casing.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56
Neutron activation log	Measures and identifies activation gamma radiation from decay of neutron-activated elements.	Can detect minute quantities of various elements (carbon, oxygen, silica, aluminum, iron, calcium, magnesium). This may be useful in determining casing corrosion or monitoring environmentally dangerous elements.	As far as is known, no high temperature and pressure tools for geothermal systems have been developed.	56

TABLE 7.2: MONITORING IN THE SATURATED ZONE

Monitoring Technique	Parameters Measured	Applications	Comments	References
Observation/ monitoring wells	Discussed below	Monitoring in the saturated zone requires wells.	Wells can be constructed in various places but some should be down gradient from the injection well. These could detect contamination from the injection well before it spreads throughout the aquifer in question.	15,53,54 55,56
Steel tape	Hydraulic head	Determination of head in a number of wells that are located in the same	Periodic measurement in non-pumping wells. In deep wells, correction for mechanical expansion and thermal contraction/expansion must be taken into account.	15
Electric sounder	Hydraulic head	See above	Periodic measurement in non-pumping wells.	15
Airline	Hydraulic head	See above	Periodic measuremnet in pumping or non-pumping wells.	15
Mechanical recorder	Hydraulic head	See above	Continuous measurements. This is advantageous for abrupt changes in water level that may occur in pump testing.	15
Contamination testing with monitoring well pumping	Groundwater quality/chemistry	If contamination is suspected from the injection well, surface facilities or reservoir-aquifer connections, pumping of monitoring wells in non-geothermal aquifers and subsequent sampling may give a quick indication of contamination.	Placing of monitoring wells close to the injection well may be an effective monitor for the integrity of the injection well.	53,56
Water sampling in non-discharging wells	Groundwater quality/chemistry	Determine either complete chemistry or individual species. If data is known on the chemistry of the geothermal fluids it may be possible to detect interaction between aquifers. Therefore monitoring of a few individual species characteristic of the geothermal fluids may indicate contamination.	Baseline characteristics must be known to interpret changes in chemistry. Characteristic species present in geothermal fluids will probably vary from place to place (if they exist). The sample will be local in nature. Various sampling tools are available.	15, 53,56
Water sampling in discharging wells	Groundwater quality/chemistry	See above	Same as above except the sample represents an average value for a larger portion of the aquifer.	15
Water sampling for introduced tracers	Either radiation or chemical species	If monitoring wells are placed throughout the aquifer and the injected waste is tagged with a tracer. Interaction will be indicated if significant levels are found at the monitoring well(s). The interaction may be due to problems with the injection well or due to aquifer-reservoir interactions.	Various tracers are available. However the introduction of a tracer such as tritium, will upset the natural content which can be used for tracing and reservoir studies. Radioactive tracers appear the most promising since they can be measured in very small quantities.	11,15,16, 18,48,53, 56
Conductivity of fluid	Conductivity, which is a measure of TDS	If geothermal fluids have significantly different TDS and mix with groundwaters with a lower TDS a change in conductance will result.	Probably best to measure on pumped samples. The natural variation in the conductance in the non-geothermal aquifer must be determined in the baseline study.	15,53
pH probe	Hydrogen ion activity	The same as above except pH is monitored.	See above	15,53
Thief sampler	Groundwater quality/chemistry	Packers enable samples to be taken from specified intervals in a well. The retrieved sample is subjected to the various chemical and physical tests discussed above.	Used in uncased wells only.	15
Temperature probe	Temperature of the fluid	Significant variations may indicate contamination by geothermal fluids.	A baseline study is needed to determine the natural temporal variations of the groundwater temperature.	15,53

TABLE 7.3: MONITORING IN THE UNSATURATED ZONE

Monitoring Technique	Parameters Measured	Applications	Comments	References
Neutron moderation or moisture logging	Slowing down and capture of neutrons.	This gives the water content of soil. If this is done at various levels in the soil the flow pattern can be determined.	The water content is obtained insitu. The presence of excess amounts of neutron moderators (Cl, Bo), may cause faulty water content determinations.	15
Tensiometers	Pressure heads in unsaturated flow.	This will allow determination of water movement in the unsaturated zone.	The values determined depend on whether the soil is wetting or drying (i.e. hysteresis)	15
Electric resistance blocks	Water content or pressure head	See above	The instrument must be calibrated for each soil. It can be calibrated for either moisture content or pressure head.	15
Psychrometers	Pressure head	See above	Can measure suction heads down to -30cm	15
Tracers	Determine water movement	Tracers could be employed to determine water movement.	Tritium has been used in the past.	15
Lysimeters (Suction cups)	Water quality/chemistry	Use as sampling devices in the unsaturated zone. Chemical changes could occur due to surface spills or leakage from surface conveyance or storage facilities.	Allows insitu soil water collection. This could be done periodically. These allow sampling only at pressure values greater than - 1 atm.	15
Salinity sensors	Specific conductance of the soil, this gives a measure of salinity	These can be used to measure changes in salinity that might occur if a surface tank or conveyance containing geothermal water was leaking into the unsaturated zone.	Allows insitu evaluation of soil salinity. Used only at pressures greater than -2 ctm. These allow continuous monitoring.	15

TABLE 7.4: MONITORING ON OR ABOVE THE SURFACE

Monitoring Technique	Parameters Measured	Applications	Comments	References
Surface water	Water quality/chemistry	Monitor to insure that neither the injection reservoir nor the surface facilities are in connection with lakes, rivers, etc.	Analysis for either tracers that have been introduced into the injection well or species that characterize the geothermal waters (Rn, As, Bo, He, Hg) in question. Baseline data is required.	5,10,11,15, 18,31,34, 39,45,51
Tank and pipeline tests	Leakage of tanks or pipes	Use of a pressurizing device and a pressure loss recorder to determine if leakage of tanks or pipelines is occurring.	Can be done routinely. The test equipment is available and the procedure is not difficult.	15
Survey networks and tiltmeters	Land movement	Land movement should be monitored to insure that no damage to surface facilities or to the injection well occur.	Land movement may occur due to various reasons. It is important to determine if movement (subsidence) is occurring due to withdrawal of geothermal fluids.	15,29,49
Siesmic network	Mechanical waves	Monitoring may prove useful if hydrofracturing is occurring due to high pressure injection or if injection is inducing earthquakes. Also many geothermal areas occur in tectonically active areas and earthquake activity may disrupt the production/injection facilities.	Seismic signals in geothermal areas may be complex and determining the exact cause of the signal may be difficult.	29,49,53
Biologic network	Chemical effects on flora and fauna	Species of certain plants and animals are known to either concentrate elements or display the effect of the element as either a nutrient or a toxin.	Geochemical methods employing flora and fauna are developed for many elements. This method for detecting contamination will probably be highly dependent on time. Its use for detecting contamination quickly is probably minimal.	28,35
Corrosion instrumentation of surface facilities	Corrosivity of fluids and conditions of materials	Monitoring of the surface facilities may help prevent breakdowns and/or surface spills.	Various devices are available on the commercial market.	19
Remote sensing (photo imagery, etc)	Light characteristics	Detection of surface spills by areal photography or sensing. A local sensor could also be placed on a tower in the area of the surface facility.	Cost effective on a regional scale, but its use on a local scale may be limited. The use of a local sensor may have applications.	15
Radon cups	Alpha particle tracks	Radon is characteristic of many geothermal systems and is used as an exploration tool. The radon cups are placed in the soil and the number of tracks due to decay are counted. This gives a measure of the amount of radon present. Since radon is mobile it may be used to detect radon contamination below the soil zone or due to surface spills.	The radon cups are commercially available. The radon cups are left in the soil for up to 4 weeks. Their use as a short term indication of contamination is limited. Although radon is a fairly mobile element its travel time from a zone of contamination to the soil zone may be fairly long.	8,59
Hg surveys	Hg content in soil vapor	Hg is characteristic of many geothermal systems. Soil vapor analysis for Hg may indicate contamination from below the soil zone or from surface facilities.	Gold film Hg detectors are commericially available and reliable. Their use depends on the presence of Hg in the geothermal waters. This method is well developed in the exploration geochemistry field. Hg is mobile, but its rate of travel is not known.	8,28
Airborne Sampling probe	Vapor & particulate matter at low altitudes or at soil-air interface	May be done from low flying aircraft or ground transport vehicles. If the geothermal system contains characteristic elements these may be detected if contamination occurs.	The instrumentation is developed and is commercially available. It is used the geochemical exploration field. Its use as a monitoring technique may be limited due to the complex nature of element interactions at the soil interface and the time dependence of contaminate migration.	8,28
Surface Geophysics				
Resistivity/electric sounding	Resistance of combined subsurface material	Monitor changes in resistance of aquifers or soil zone.	Well developed technique. Numerous instruments are available commerically. Date interpretation may be difficult in complex geologic areas. Ability to detect deep groundwater contamination is unknown, but doesn't appear promising. Ability to track shallow groundwater contamination movement has been demontrated.	15,23,53 56
Seismic refraction and reflection	Velocity determination of compressional waves in subsurface medium	The changes in either density or saturation may be detected. This could be used to determine deep movement of contaminated water or movement of the injected fluid in the injection defining aquifer dimensions.	Instrumentation is commercially available. Interpretation of data (especially reflection) can be difficult. The sensitivity may not be great enough to monitor contamination movement.	2,6,15,30 53,56
Gravity	Gravitational acceleration	It can be used to monitor changes in surface elevation due to ground movements. It may be possible to determine changes in density in fluids at depth and thus contamination.	Commercial instrumentation is available. The sensitivity of the instruments for monitoring contamination is probably too low.	17,36,56

should be incorporated in an overall monitoring plan, since preventive maintenance of surface facilities does not necessarily insure that contamination will not occur through other contaminant routes.

Various methods are available for "preventive monitoring." Monitoring of the injection well appears to be promising since the injection well has a high potential to connect geothermal fluids and groundwater. The most promising techniques for monitoring the injection well are borehole geophysics and annulus fluid properties.

Borehole geophysical methods can be used periodically on injection wells. Various instruments have been developed for use in geothermal wells. One of these, the acoustic borehole televiewer, allows the well to be checked for excessive corrosion, scaling, or fractures in situ. Flowmeters and cement logs have also been developed for geothermal conditions and will aid in determining leakage from the well.

The annulus fluid can be monitored continuously with conductivity probes, temperature probes, pH probes, Eh probes, pressure gauges, etc. If rapid variations in the physical/chemical properties are detected, leakage may be occurring through the well casing. This is a simple but effective monitoring method.

Monitoring of the physical or chemical properties of the fluids in the saturated or unsaturated zones may be used to detect contamination that has already occurred. However, there are two important points to consider. The first is the time required for the contamination to be sensed by a given monitoring device, and the second is the sensitivity of the monitoring device to the physical or chemical property under scrutiny.

The use of monitoring wells in the groundwater aquifer near the injection or production well should be able to detect contamination quickly. If enough chemical or physical contrast exists between the fluids, it may be possible to continuously monitor the system with conductivity probes, specific ion probes, or temperature measurements.

Periodic water samples from wells may also be used to detect small variations in chemistry over a long period of time. If significant deviations occur that cannot be attributed to a surface source or to contamination from the injection well, it may be that the aquifer-reservoir systems are hydraulically connected.

The use of surface geophysical techniques, such as resistivity, may have applications in monitoring the groundwater system; however, the sensitivity of such systems is highly dependent on the depth of contamination and the chemical and physical contrast between the fluids in question.

Surface geochemistry techniques such as radon and mercury detectors may have applications in monitoring. Both mercury and radon are fairly common in geothermal systems and have high enough mobility that they can migrate upward from the source of contamination. However, it may be a considerable period of time before a noticeable change in concentration occurs. Surface geochemistry techniques appear to be suited to long-term monitoring as opposed to the short-term.

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SECTION 8

NONDISPERSIVE CONTAMINANT TRANSPORT MODEL

INTRODUCTION

Background

The development of a monitoring methodology requires the design and placement of observation wells in the aquifer system that is to be monitored. In a typical area where geothermal power is to be exploited, the heat is derived from deep aquifers that are generally not potable. Even if they were, the water source would normally be too deep to be economically useful for domestic and agricultural purposes. In addition, if spent geothermal waters are to be injected into the original deep aquifer, the injected fluids will have water chemistry similar to that of the host fluid. For these reasons, potential contamination and monitoring of the geothermal reservoir is not a problem that is to be addressed in this section.

The typical geothermal reservoir in the Great Basin is normally overlain by near surface potable aquifers that are used for domestic, agricultural and/or industrial purposes. It is possible to contaminate these aquifers with geothermal fluids of poorer quality than the host fluid. This contamination can enter the aquifer through various interfaces. Some of the most common include:

1. Leakage from injection wells designed to return the geothermal fluid to the geothermal reservoir.
2. Accidental spills from the geothermal plant.
3. Infiltration from holding or evaporation ponds.

Monitoring of pressure in injection, pumping, and observation wells is the quickest way to detect significant leaks in injection wells. The pressure propagation is nearly instantaneous compared to the time it takes to transport contaminants to monitoring wells. Adequate pressure monitoring in the appropriate hydrologic systems can therefore be a quick and efficient way of detecting injection well leaks before any significant contamination takes place. However, small leaks may not produce detectable pressure changes, or these changes may be difficult to detect. In addition, contamination from surface ponds or surface spills will not be detectable from pressure monitoring of the aquifer. Finally, once a leak has been detected, monitoring wells will be more useful in determining the extent of the aquifer contamination rather than simply detecting the fact that there is a leak.

For these reasons, it is desirable to have a network of monitoring wells from which water quality data can be collected. The design methodology of such a network is primarily the subject of this section. The design of a monitoring well network is achieved by taking into consideration several important criteria.

The monitoring network should be reliable from two standpoints: first, the wells should be well-built to insure long life and reliable service; second, they should be placed in such a way as to insure that potential contaminant plumes will be intercepted in detectable quantities. Reliable service is a physical consideration that will not be addressed in this section. Reliable interception of a contaminant plume can be achieved by accurate information and simulation of the aquifer hydraulic responses and contaminant transport.

The monitoring well network should be efficient and cost-effective. It is always possible to design a monitoring network with numerous very closely spaced wells that will reliably detect leaks from geothermal systems. This approach would probably not be efficient and cost-effective. Given adequate knowledge of contaminant pathways and travel times, a few strategically placed monitoring wells should provide enough information to monitor the aquifer with reliability approaching that of a costly network of numerous closely spaced wells.

In order to achieve a monitoring network that satisfies the above mentioned criteria, it is important to have a groundwater solute transport model of the potable aquifer system above the geothermal reservoir. Such a model will allow the analyst to determine pathways, travel times and contaminant concentrations in the aquifer and at pumping wells and other groundwater discharge areas.

There are several different methodologies available with which to model solute transport in aquifer systems. The methodology chosen for a particular task depends upon the type and amount of data available for modeling use and the overall objectives of the task in question. The general task addressed in the report is (as previously mentioned) to develop a methodology for a reliable, efficient and cost-effective monitoring system for aquifers that may potentially be contaminated. In addressing this task for a specific case, there are several constraints that the analyst will, in most cases, be working under, and there are several objectives that will tend to be universal and independent of the specific study area. These constraints and objectives need to be examined in order to choose the type of model that will be best suited for use in designing the appropriate monitoring network.

The constraints that the analyst will be working under include the following: lack of hydrologic data; limited accuracy of solute transport models; limited time to study various scenarios of well placement; limited computer resources and/or limited financial resources to pay for computer time in running the solute transport models.

The hydrologic data necessary for solute transport modeling may include all, or some combination of the following: hydraulic conductivity, porosity, piezometric head, aquifer thickness, aquifer geometry, recharge, pumping and injection rates, and longitudinal and transverse dispersivities. Typically, a few spot measurements for most of these parameters are available, but it is seldom that detailed distributed measurements are available. In particular, dispersivity data are almost never available.

For most types of solute transport models, accurate values for these parameters are necessary in order to get a reliable predictive simulation. In a typical area being considered for a geothermal power plant, hydraulic parameters for the reservoir will probably be relatively well known, but the shallow potable aquifers will generally be ignored unless it is specifically planned to inject geothermal fluids into them.

The limited time available for study and limited computer and financial resources also play important roles with respect to constraints on the hydrologic analyst attempting to design an efficient, reliable monitoring network. Most solute transport models require large amounts of time to prepare input data and they require very large amounts of computer time to run each scenario. In addition, they usually produce voluminous amounts of output of contaminant concentrations, piezometric heads, velocities and other data which takes a large amount of time to analyze.

The result is that a huge investment can potentially be made using solute transport models for design of monitoring networks. Most solute transport models in common use suffer from the above-mentioned constraints because they solve the advective-dispersion equation for conservation of solute mass. It is the solution of this equation that provides predictive values for contaminant concentration.

The objectives to be met for the purpose of designing a monitoring network may not necessarily require all of the information that is produced by an advective-dispersion solute transport model. The questions that generally need to be answered for monitoring network design include:

1. What are the contaminant pathways?
2. How fast are the contaminants being transported?

3. When will they arrive at critical discharge areas?
4. What will the contaminant concentrations be at critical discharge areas?

These questions are similar to those addressed by Nelson (1978a,b,c,d). He determined that it is often not necessary to use models that solve advective-dispersion equations to answer these questions. It therefore seems reasonable that it may not be necessary to use advective-dispersion models to meet the basic objectives of designing a reliable, efficient monitoring system for aquifers that will be potentially subjected to pollution from geothermal development.

Summary of Model Development

A computer program was developed during the course of this study which attempts to answer the questions and address the criteria discussed in the introduction. The selection of the modeling scheme, or algorithm, for the program was done in light of historical and recent advances and thinking with respect to the modeling of solute transport phenomena. A review of the literature pertaining to these advances and how the literature influenced the choice of the modeling scheme is presented in the following section on solute transport and advective-dispersion.

The model developed solves the steady-state groundwater flow equations subject to certain constraints, assumptions and boundary conditions. These assumptions and conditions have been carefully chosen to provide maximum utility and minimum complexity for the typical hydrogeologic system that might be encountered in geothermal areas. The solution to the flow equations provides velocity fields which are used to track solute particles though the use of complex potential theory.

The model calculates and plots information which is very useful to the analyst in determining potential flow paths for contaminants. The model plots maps of streamlines, equipotentials and isochron lines. In addition, the program plots solute concentration arrival time distributions for any pumping wells in the study area. This information can be used effectively by the analyst in making decisions about the distribution and number of injection wells necessary for the study area to optimize monitoring for geothermal leaks. In many situations, simple placement of monitoring wells down-gradient from an injection well may in fact not intercept a contaminant plume or leak. This could be due to a variety of factors, including anisotropy, boundary conditions, local flow deviations due to other pumping and/or injection wells, etc. With only a minimum amount of hydrologic information, the analyst can use the graphical output from this model to more efficiently and intelligently place monitoring wells for different field scenarios.

The model has been designed to allow several complications that may be present in the study area, while trying to keep the amount of hydrologic data necessary to a minimum and to keep the solution algorithm as efficient and fast-running as possible. For instance, the model could have been designed to handle a nonhomogeneous aquifer (or an aquifer of varying thickness), however, nonhomogeneity would have required the solution of a system of equations with nodal values for numerous points. Solving a system of equations would have required that the program use large amounts of computer memory and much more computer time than would have been otherwise necessary. By making the assumption of a homogeneous aquifer, the streamlines can be found by numerically solving ordinary differential equations, a much simpler task in terms of computer time and memory. In addition, in order to accurately model a nonhomogenous aquifer, the spatial distribution of the transmissivity function must be known, and that knowledge is seldom available. Of course, an error may be made by assuming homogeneity, but for the design purposes of this model (monitoring well placement), this potential error is not considered important.

Anisotropy (the ratio of horizontal to vertical transmissivity, Txx/Tyy, is a measure of anisotrophy) is a more important feature to consider than nonhomogeneity in terms of monitoring well placement because in an anisotropic aquifer, the velocity vector is not necessarily colinear with the gradient vector. In other words, monitoring wells placed down-gradient from an injection well in an anisotropic system may not intercept a contaminant leak. Because of this phenomenon, anisotropy is a feature built into the model. The aquifer may be isotropic, or it can have constant anisotropy or the anisotropy can vary linearly with position (i.e., the ratio of Txx/Tyy can be specified as a linear analytic function).

The model treats contaminants as nondispersive so that all transport that takes place is strictly advective. Dispersion could be handled by use of the Method of Characteristics (MOC), in which the advective portion of transport is still handled the way it is presently and dispersive transport could be taken care of by a finite element or finite difference scheme. This, of course, would require more computer memory and time for the dispersive transport. In addition, dispersion primarily affects the first arrival time and the concentration distribution times of the contaminants. These two factors are not as important in monitoring well placement. The primary concern in monitoring well placement is generally contaminant flow directions and maximum concentration distributions, both of which are questions that can be handled by a strictly advective transport scheme. Moreover, a dispersive model requires dispersivity values for the aquifer, data which are seldom available, especially on a reconnaissance basis. A more complete discussion of the question of dispersive transport can be found in the next section entitled Solute Transport and Advective-Dispersion.

Boundary conditions such as impermeable boundaries and constant head boundaries can significantly affect flow directions and velocities of contaminants. Included in the model is the capability to have constant head and/or impermeable boundaries in any orientation. The ability to handle boundary conditions was included through use of image well theory and simple geometry so that the model complexity was not significantly affected by this feature.

In the following sections, various types of models are reviewed and an historical review of solute transport modeling is provided. This will allow the reader to get a clearer and more detailed understanding of the type of model chosen and developed for this project.

Solute Transport and Advective-Dispersion

Groundwater contaminants (or solute), generally move with the ambient groundwater, away from the depositional site. However, contaminants have components of flux other than that of the strictly advective (pressure induced) ambient groundwater flux. These additional components of flux may significantly affect the size, shape, and concentration distribution of the contaminant plume. These additional components of flux can be loosely referred to as dispersion. Dispersion is defined and discussed below with an emphasis on numerical simulation of dispersive transport and problems related to dispersion coefficients.

Fried and Combarnous (1971, p. 176) defined dispersion as "the occurrence and development of a transition zone between two domains of the fluid phase with different compositions". The transition zone is the region where the concentration of one fluid varies from some initial contaminant concentration to an undetectable or background level. The transition zone results from the combined effects of molecular diffusion and mechanical dispersion.

Molecular diffusion is caused by the tendency of an aqueous system to obtain a uniform chemical concentration. This property is referred to as Fick's Law and is due to the chemical potential gradient between fluids of different ionic concentrations. Molecular diffusion is independent of fluid movement, existing when fluid is in motion or at rest.

Mechanical dispersion of a solute within an aquifer is primarily influenced by velocity variations of the fluid. These variations may be caused by pore size variations and aquifer heterogeneities. On a microscopic scale, smaller pore size will cause solute to move faster (Figure 8.1a) for a given quantity of

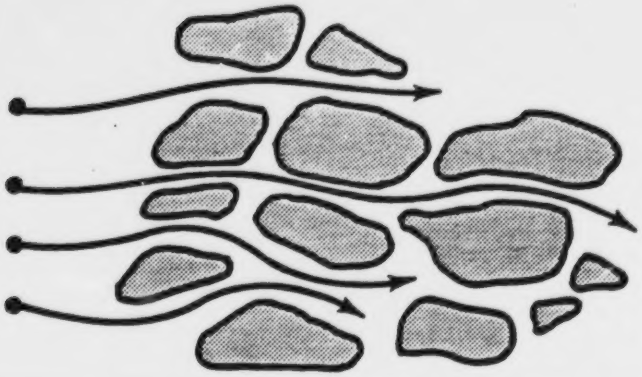

Figure 8.1a Pore size variations contributing to mechanical dispersion

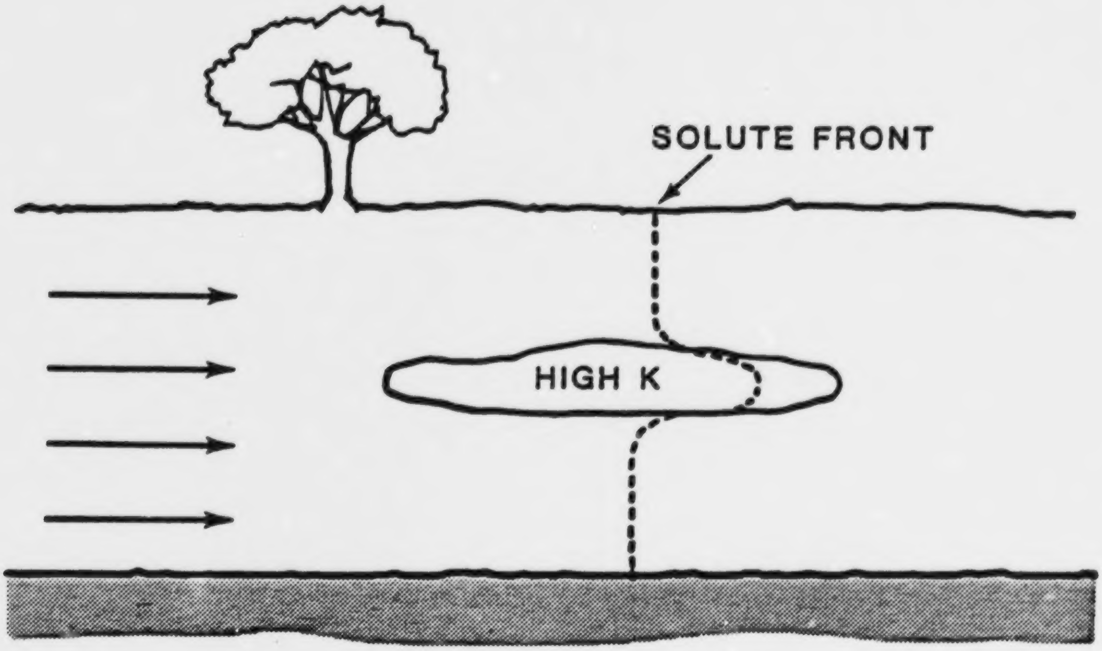
SOLUTE FRONT
HIGH K

Figure 8.1b Aquifer heterogeneities contributing to mechanical dispersion

solute. Macroscopically, stratigraphic lenses of higher (or lower) hydraulic conductivity may cause solute to travel faster (or slower) through these lenses than through the rest of the aquifer, transporting some solute beyond the solute plume (Figure 8.1b). The effect of these processes creates a transition zone at the perimeter of the plume where the groundwater/contaminant interface becomes smeared. Analyses of contaminant flux often consist of summing the dispersive flux with the advective flux to determine the concentration gradient of the contaminant as it varies with time at a specific location. Dispersive flux is caused by mechanical dispersion and molecular diffusion of a solute. The component of this flux oriented along the axis of flow is called longitudinal dispersion (D_L), while that component orthogonal to the axis of flow is called transverse dispersion (D_T).

Bear (1979) presents the general equation for contaminant flux in a homogeneous medium. In Cartesian coordinates for two dimensions the equation, generally known as the advection-dispersion equation, is

$$P \frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left[P\left(D_{xx} \frac{\partial c}{\partial x} + D_{xy} \frac{\partial c}{\partial y}\right)\right] + \frac{\partial}{\partial y} \left[P\left(D_{yx} \frac{\partial c}{\partial x} + D_{yy} \frac{\partial c}{\partial y}\right)\right] - q_x \frac{\partial c}{\partial x} - q_y \frac{\partial c}{\partial y} \qquad (8.1)$$

which can be written using Einstein's Summation Convention

$$P \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i} \left(P\, D_{ij} \frac{\partial c}{\partial x_j}\right) - q_i \frac{\partial c}{\partial x_i} \qquad (8.2)$$

or

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial c}{\partial x_j}\right) - v_i \frac{\partial c}{\partial x_i} \qquad (8.3)$$

where $v_i = q_i/P$,
$i = 1,2$,
and $j = 1,2$.

The variables are defined as: porosity (P), solute concentration (c), time (t), Darcy discharge (q), velocity (v), and the dispersion coefficient (D).

The dispersion coefficient D is commonly treated as a second rank tensor. If a two-dimensional isotropic medium is assumed, the dispersivity tensor can be greatly simplified (Bear 1961) where

$$D_{xy} = D_{yx} = 0, \; D_{xx} = D_L = \alpha_L v, \text{ and } D_{yy} = D_T = \alpha_L v.$$

α_L and α_T are longitudinal and transverse dispersivities, respectively; v is groundwater velocity; x is the longitudinal direction and y is the transverse direction.

Equation 8.3 can be rewritten for an isotropic media and unidirectional flow in the x direction as

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} + D_T \frac{\partial^2 c}{\partial y^2} - v \frac{\partial c}{\partial x} . \tag{8.4}$$

Where there is no lateral (transverse) dispersive flux, or for one-dimensional contaminant flow, Equation 8.4 becomes

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} . \tag{8.5}$$

Numerical Solutions and Problems

Previous to the 1960's, solutions of the solute transport equation were generally limited to those solutions that could be found by analytical techniques. These solutions were for simplistic problems and required tedious analytical manipulations. In the mid 1960's, with the rapid development of computer technology, numerical techniques for solving the solute transport equation began to develop. These techniques enabled researchers to solve groundwater problems of greater complexity than were previously solvable, and with less time.

Peaceman and Rachford (1962) modeled two dimensional flow of miscible fluids. Pressure distributions within the flow field were computed at every time step. From each pressure distribution, velocity was calculated at each point. Using these velocities, the new concentration distribution for the following time step was calculated with a finite difference approximation of the solute transport equation (Equation 8.4).

Gardner et al. (1964) employed the Method Of Characteristics (MOC) for the same problem. The MOC keeps track of a distribution of discrete water "particles" and calculates the flux components on each particle. The advective velocity components on each particle are obtained at each time step by the method given by Peaceman and Rachford (1962). The dispersivity components on each particle are then approximated using a finite difference solution to the solute transport equation.

Stone and Brian (1963) developed a numerical scheme to solve the one-dimensional contaminant transport equation (Equation 8.5). They used a weighted finite difference method with arbitrarily weighted terms assigned to the time and advection terms to better approximate an exact solution.

Shamir and Harleman (1967) wrote the dispersion equation in terms of $\Phi - \psi$ (potential - stream function) coordinates and then used the Stone and Brian (1963) scheme for one-dimensional flow. The use of $\Phi - \psi$ coordinates kept the longitudinal orientation of the contaminant plume oriented along the ψ axis eliminating the need for cross-diagonal dispersivity terms. Lateral (transverse) dispersion was calculated by an Alternating Direction Implicit (ADI) numerical scheme.

During the 1970's numerical modeling of the solute transport equation was principally performed using the Method of Characteristics, the Finite Difference Method, and the Finite Element Method. Although these three numerical techniques showed rapid evolutions, the basic solute transport equation (Equation 8.1) did not change. Early in the 1970's, numerical simulations of contaminant flux were compared to results from field studies and laboratory experiments. Discrepancies were found which were attributed to the dispersivity coefficients of the solute transport equation. These discrepancies made accurate numerical simulation of contaminant flux, and reproduction of field and laboratory results, very difficult.

Discrepancies in determining dispersion coefficients were found when results from laboratory experiments were compared with actual field measurements. Bear (1961) performed laboratory experiments to determine a dispersion coefficient and found it to be on the order of 10^{-2}cm. Field experiments have shown that the coefficient of dispersion (in this case D_L) can be as much as six orders of magnitude greater than those values found in a laboratory for a similar porous media (Pickens and Lennox, 1976). The dispersivity coefficients determined from field measurements reflect the nonhomogeneities of the aquifer while laboratory experiments were carried out with small-scale homogeneous porous media. The differences in scale between the laboratory and field media appear to be the cause of the coefficient discrepancies.

Fried (1975) defined four levels at which to measure field dispersivities: a local scale (2-4 m), two global scales (4-20 m, and 20-100 m), and a regional scale (>100 m). A different experimental technique was recommended at each scale. He concluded that dispersivity is dependent upon field scale.

Schwartz (1977) found that in certain heterogeneous systems, it was not possible to define a single value for dispersivity which would simulate the system response. Heterogeneities within an aquifer would cause the dispersion coefficient to vary with the location of measurement.

Many of the methods above were field calibrated by deciding upon a dispersion coefficient that best fit the model output to field measurements. This coefficient is not necessarily applicable for different field scales and different computer scenarios.

The scale dependence of dispersion is indicative of a basic problem with the assumptions taken in deriving the advective-dispersion equation. The dispersive flux term is assumed to be proportional to the velocity and the concentration gradient. This assumption appears not to be valid for large-scale problems of solute transport. Local variations in hydraulic conductivity appear in many cases to be responsible for the observed dispersion solute flux. Because of these conductivity variations, the models using advective-dispersion equations for solute transport simulation are calibrated by trial-and-error (matched with field data) and the dispersivity values determined may not have any long term predictive value. Reddell and Sunada (1970) concluded that "dispersion is not worth worrying about except for the most noxious pollutants and radioisotopes...". For accurate prediction of contaminant migration, sufficient and reliable data on velocity distributions and dispersivities must be obtained for input into the solute transport equation. However, to date there are no standard, adequately tested techniques of acquiring velocity and dispersivity data (Anderson, 1979, p. 122).

Current research by Smith and Schwartz (1981) seems to indicate that classical theory pertaining to dispersion is no longer valid. They contend that the diffusion model for macroscopic dispersion may be inadequate to describe solute mass transport in geologic units. Dispersion occurs because of macroscale changes in the magnitude and direction of groundwater flow. These changes may be caused by the effects of sources and sinks, aquifer heterogeneities, and aquifer boundary conditions.

Previous attempts at numerical solutions of the solute transport equations for highly dispersive solutes have been rough approximations. Numerical errors are also incorporated into these approximations in the form of overshoot and "numerical dispersion" (Figure 8.2). Numerical dispersion, as previously explained, is the apparent but ficticious dispersion that occurs when a first order derivative is approximated numerically. Overshooting (and undershooting) is oscillation of a solution as an abrupt front is approached from its upstream (or downstream) side (Bear, 1979). Both the Finite Element Method and the Finite Difference Method are susceptible to overshoot and numerical dispersion, although the Method of Characteristics is not very susceptible to overshoot.

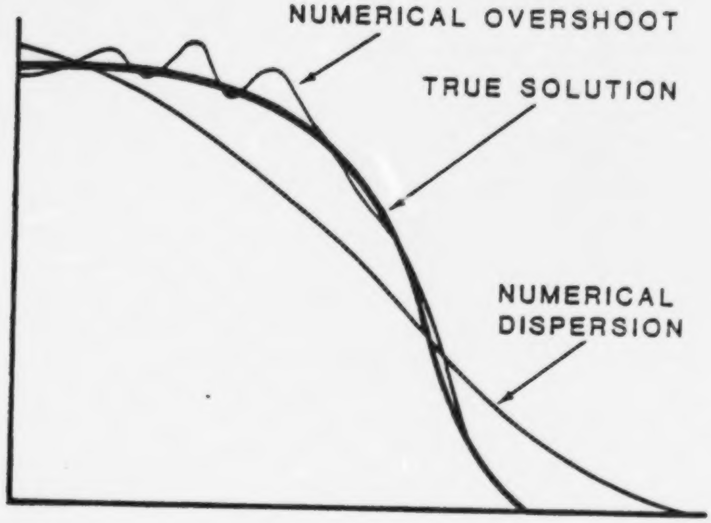
NUMERICAL OVERSHOOT
TRUE SOLUTION
NUMERICAL
DISPERSION

Figure 8.2 Examples of numerical overshoot and numerical dispersion

Alternatives: Advective Solute Transport Models

Many studies have been undertaken which have ignored dispersion and consider only immiscible groundwater flow. Immiscible flow equations are formulated without dispersive flux terms and are a function of advective flux only.

In the Tahal study (Harpaz et al., 1968), which involved artificial recharge and recovery, solute injected into the aquifer was assumed immiscible with the surrounding ambient groundwater. Analytical solutions were developed for the groundwater divide (caused by a pumping well in a uniform flow regime), as well as a solute (contaminant) frontal position which varied with time. These solutions were for a single well of a dipole configuration in a homogeneous isotropic aquifer with a uniform ambient flow field.

A similar study was conducted by Gringarten and Sauty (1975) where thermal waters were stored in an aquifer and then pumped out. The process of heat transfer from the thermal fluid to the aquifer matrix is analogous to adsorption. Thermal dispersion (the presence of a thermal gradient or transition zone) was ignored and thermal frontal positions were calculated as the frontal position varied with time.

Another study concerning solute travel times to wells was undertaken by Kirkham and Affleck (1977) which also assumed immiscible flow. This study was strictly analytical and travel times were obtained for three different cases (single well - homogeneous; single well - concentric nonhomogeneity; river to well - homogeneous). Solute travel times for the different cases were calculated yielding simple isochronal distributions.

Nelson (1978a,b,c, and d) in a series of papers on the environmental consequences of groundwater contamination, introduced the concept of contaminant arrival distributions in a homogeneous isotropic aquifer. He addressed the questions of:

1) Where are the contaminants?
2) When will they arrive at a specific location?
3) How much contaminant will be at the point of uptake?

The information derived from Nelson's papers can serve as basic input to the solution of many groundwater contaminant management problems (Bear, 1979). The contaminants considered by Nelson were nondispersive and conservative.

Charbeneau and Street (1979) conducted a similar study using the Finite Element Method and distinguished their study from Nelson's (1978) by incorporating the complexities of a nonhomogeneous aquifer system, and therefore creating a more versatile model. The FEM computations require somewhat greater computer processing time, storage, and data than the more efficient numerical method used by Nelson, who provides an easy and quick way of obtaining a preliminary analysis of a hydrogeologic system. Mercer and Faust (1980, p. 113) suggest that sometimes complex models are used too early in a study.

> For example, for a hazardous waste problem, one generally should not egin with a solute transport model. Rather the first step is to be sure the groundwater hydrology (velocity) in particular) can be characterized satisfactorily, and therefore one begins to model the groundwater alone.... A general rule might be to start with the simplest model and a course description of aquifer performance is obtained.

Nelson's (1978a,b,c, and d) algorithm fulfills the above requirements and more. The amount of initial data needed is minimal. The output consists of a contaminant location distribution as well as a frontal distribution with time. The frontal and contaminant location distributions are based on the assumption that the contaminant is immiscible with the ambient groundwater (and therefore dispersion is ignored). Injection and pumping well locations and scenarios can be changed with minimal user effort and time.

> Once this information is made available to the planner, he can control the movement of the contaminants in the aquifer by controlling (say, via pumping and recharge operations) the flow pattern in the aquifer and/or initiate corrective measures to protect the environment endangered by the outflow of contaminanted groundwater (Bear, 1979, p. 299).
>
> The goal in using an advection model is not to provide a detailed description of the extent and configuration of the contamination plume for which consideration of dispersion may be necessary, but to estimate the average changes in water quality often on a regional scale or to determine solute travel times to a well or discharge area (Anderson, 1979, p. 132).

For these reasons, Nelson's algorithm (with modifications detailed) is particularly well-suited for the purposes of planning a monitoring network in a geothermally developing area.

Nelson's (1978) study (or model) has been cataloged (Bachmat, et al., 1978) with other groundwater models ranging from relatively simple models to the most advanced state-of-the-art models. It reportedly has been used in various studies such as:

* Initial model of accidental release from a fuels reprocessing facility in South Carolina.
* Initial evaluation of accidental failure of earthen sewage holding ponds, Kennewick, Washington.
* Used during short course by Agricultural Research Services, Chickasha, Oklahoma.
* Example evaluation for the State of Idaho Department of Water Administration.
* Evaluation of a numerical generation scheme for pathlines in cooperation with Battelle Northwest Laboratories for the United States Energy Research and Development Agency (ERDA) now DOE (Department of Energy).
* Evaluation of potential hazard from subsurface reactor accidental releases from Sandia Laboratories, Albuquerque, New Mexico (Bachmat et al., 1978).

Goals and Objectives

The purpose of this part of this study is to develop a computer groundwater flow model that is quick running, demands little computer memory, and can simulate an isochronal distribution and flow path map of a contaminant plume resulting from potential geothermal fluid leaks. Nelson (1978b) developed a computer groundwater flow model that satisfies these criteria but is only applicable to a small range of groundwater flow model problems. The focus of this research was to modify and expand the versatility of Nelson's algorithm to be applicable for groundwater studies involving fields of injection and pumping wells resulting from geothermal power plant activities.

The Nelson algorithm includes several terms that account for flow into a cylinder of infinite hydraulic conductivity (such as a lake or pond). Since these terms are a function of the square of the well radius, they are insignificant when applied to wells of small radii. Deletion of these terms from Nelson's algorithm would result in a simplified form of the algorithm without detracting from its accuracy.

Nelson's algorithm intrinsically assumes a uniform flow field parallel to the x axis (west to east) whereas the flow field in a study area may be of any orientation. Therefore a transform must be employed to rotate a uniform flow field of any orientation into an alignment parallel to the x axis.

The model developed by Nelson is valid for only isotropic homogeneous aquifers of an infinite areal extent. Since most aquifers do not meet these criteria in that they may be anisotropic, non-homogeneous, and/or of finite areal extent, they must be transformed into imaginary isotropic homogeneous aquifers of infinite areal extent to accommodate the Nelson algorithm.

Aquifer anisotropy is accounted for by transforming the anisotropic aquifer into an isotropic aquifer (see following subheading). This transform was developed and used in conjunction with Nelson's algorithm.

Often an aquifer cannot be considered to have infinite areal extent due to the presence of a constant head boundary (such as a stream or a lake), or an impermeable boundary. These types of boundaries are particularly prevalent in the Great Basin area of Nevada and Utah where geothermal power development is expected to be concentrated. Nelson's algorithm has been modified so that aquifer boundaries may be simulated through the use of image wells (see following subheading).

Most aquifers are nonhomogeneous due to variations in hydraulic conductivity and/or aquifer thickness. A transform scheme needs to be developed to numerically transform a nonhomogeneous aquifer into a homogeneous one (with constant hydraulic conductivity and thickness).

Many of the above aquifer variations can be found in already existing Finite Element and Finite Difference groundwater computer models that solve advective-dispersion equations. But these models are cumbersome to use, require large amounts of data, computer memory, and CPU time. If the hydrogeology of a study area is not clearly defined, these data are usually inaccurate and/or incomplete. The equations generated by Nelson's algorithm are ordinary differential equations and can be solved using ordinary differential equation numerical techniques such as the Runge-Kutta Method. Thus the contaminant arrival and distribution information can be calculated with at least an order of magnitude less CPU time and central memory using Nelson's algorithm instead of solving the advective-dispersion equation with finite element or difference techniques. This is a tremendous advantage for designing monitoring networks for aquifer systems potentially affected by geothermal power development.

Specifically, the modifications and extensions examined in this study are:

1. Certain simplifications of Nelson's algorithm.
2. Incorporation of a directionally variable uniform flow gradient.
3. Development of a numerical transform to account for aquifer anisotropy.
4. Simulation of impermeable and equal potential boundaries through the use of image wells.
5. Development of a transform or numerical scheme to account for aquifer nonhomogeneities.

The above modifications should ensure a more versatile and practical model for describing groundwater flow regimes. The resulting algorithm, POLLUTE, should prove to be a valuable tool in simulating potential groundwater contamination problems for design of geothermal monitoring networks.

PATHLINE ADVECTIVE MODEL CHARACTERISTICS AND ABILITIES

Introduction

Nelson (1978b) developed an advective model for use in simulating groundwater flow for an aquifer with injection and/or pumping and a uniform flow from the west. This algorithm was used as a starting point and modified considerably. Some modifications extend and generalize while others simplify the resulting capabilities of the program developed from the modified advective model. The program produced for this report that solves the modified set of advective flow equations is called POLLUTE. The derivation of the basic set of advective flow equations and subsequent modifications are presented in this section. Examples of various well field scenarios are used to show what effects the modifications have on a reference well field scenario. The reference well field scenario consists of an injection and pumping well within an isotropic homogeneous aquifer of uniform thickness and infinite areal extent (Figure 8.3). The ambient flow regime is constant and flows from left to right (west to east). The pumping well is located approximately 750 feet down the uniform flow gradient (although not directly down gradient) from the injection well. All well field scenarios presented in this chapter are the same, unless otherwise noted.

Basic Derivations

The derivation of the algorithm was based on complex variable theory and Darcy's law. The complex components for a uniform flow gradient, for sources and sinks, and for flow into a cylinder, were summed resulting in the complex potential $\Omega(z)$. The potentiometric and stream functions (Φ and Ψ) are determined by separating the complex potential into its real and imaginary parts. The potentiometric function Φ defines the piezometric head of the groundwater for any (x,y) location in the area studied. The stream function Ψ defines the path of groundwater flow and is everywhere orthogonal to the potentiometric function. The gradient (in two dimensions) of the potentiometric function is simply the gradient term ($\nabla\phi$) found in Darcy's law ($q = -K\nabla\phi$). The algorithm is composed of the velocity components of the specific discharge in the x and y directions $\left(q_x/P \text{ and } q_y/P\right)$.

The complex components (Ω_s) for sources and sinks are

$$\Omega_s = \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \ln Z, \qquad (8.6)$$

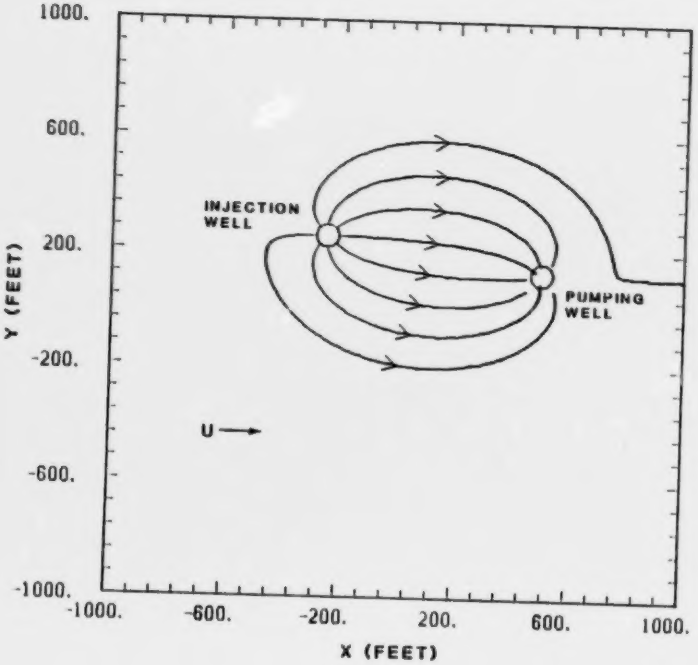

Figure 8.3 Reference scenario for comparison

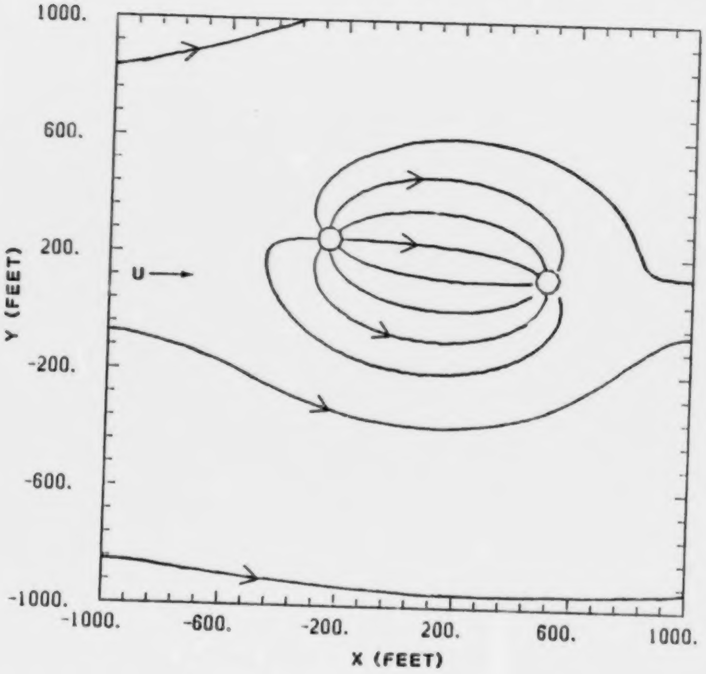

Figure 8.4a Flow lines for dipole well system and a uniform flow direction of 270°

and for a uniform gradient with flow into a cylinder (Ω_c)

$$\Omega_c = -U\overline{Z} + \frac{ur_o^2 \quad z}{(x-x_o)^2+(y-y_o)^2} \ . \qquad (8.7)$$

Q_j is the well discharge, r_o is the cylinder radius, x_o and y_o locate the cylinder in a cartesian plane, U is the uniform flow gradient, D is the saturated aquifer thickness, K is the aquifer hydraulic conductivity, and n is the total number of wells. The complex variable Z is defined as $Z = X + iY$ and $Z = \rho\, e^{i\theta}$, where ρ is a dimensionless term representing the radial distance between some point and a predetermined location.

In the derivation of Nelson's algorithm, ρ is defined as

$$\rho = \frac{r}{r_{well}}$$

for a well located at the origin. r is the radial distance between some point and that well and r_{well} is the well radius. For all other wells, ρ is defined as

$$\rho = \frac{r-a_j}{(x_j{}^2-y_j{}^2)^{1/2}} \quad ,$$

where $r-a_j$ is the radial distance between some point and that well, and where x_j and y_j are the location coordinates of that well.

Expanding equations 8.6 and 8.7 and separating into real and imaginary parts yields

$$\begin{aligned} \phi = -Ux &+ \frac{Ur_o{}^2(x-x_o)}{(x-x_o)^2+(y-y_o)^2} \\ &+ \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \ln \left(\frac{(x-x_j)^2+(y-y_j)^2}{\left(x_j{}^2+y_j{}^2\right)} \quad {}^{1/2} \right) \end{aligned} \qquad (8.8)$$

and

$$\psi = Uy + \frac{Ur_o^{\,2}\,(y-y_o)}{(x-x_o)^2+(y-y_o)^2} + \sum^{n} \frac{Q_j}{2\pi DK} \tan^{-1}\left(\frac{y-y_j}{x-x}\right). \qquad (8.9)$$

Taking the gradient of ϕ and applying Darcy's law where $v = -(K/P)\nabla\phi$;

$$\frac{dx}{dt} = \frac{KU}{P}\left[1 - \frac{r_o^{\,2}}{(x-x_o)^2+(y-y_o)^2}\left(1 - \frac{2(x-x_o)^2}{(x-x_o)^2+(y-y_o)^2}\right)\right] + \sum_{j=1}^{n} \frac{Q_j}{2\pi DK}\left(\frac{x-x_j}{(x-x_j)^2+(y-y_j)}\right)^2 \qquad (8.10)$$

and

$$\frac{dy}{dt} = \frac{2KU}{P}\left[1 - \frac{r_o^{\,2}(x-x_o)(y-y_o)}{\left((x-x_o)^2+(y-y_o)\right)^2}\right] + \sum_{j=1}^{n} \frac{Q}{2\pi DK}\left(\frac{y-y_j}{(x-x_j)^2+(y-y_j)^2}\right). \qquad (8.11)$$

Equations 8.10 and 8.11 are a slightly varied form of Nelson's algorithm and they assume that only the first well is of sufficient radius to warrant treatment (i.e. the component for flow into a cylinder) of flow into it. Nelson's first well was actually a pond of large radius and therefore required special attention (see next section). Since the component for flow into a cylinder is a function of the square of the radius of the cylinder (as seen from Equation 8.7), that component tends toward zero as the cylinder radius gets small. If all wells (cylinders) in the study area are of small radii compared to the field scale, the component for flow into a cylinder (or well) is negligible and can be ignored. The model developed here assumes the component for flow into a cylinder is negligible in all cases.

The Thiem equation for confined groundwater flow near a source or sink is

$$\phi = \frac{Q}{2\pi DK} \ln\left(\frac{R_{inf}}{r}\right) \qquad (8.12)$$

where R_{inf} is the radius of influence, and is very similar to the source/sink term in Equation 8.8. Our model assumes the Thiem equation to be valid for all sources and sinks and therefore ρ (refer to previous section) is defined as

$$\rho = \frac{R_{inf}}{r-a_j}$$

to more closely conform to the Thiem equation. The Thiem equation is valid only for r greater than zero and less than or equal to R_{inf}. Where r is greater than R_{inf}th source/sink term is ignored.

By disregarding the component of flow into a cylinder and incorporating the redefined ρ, Equations 8.8 and 8.9 become

$$\phi = -Ux + \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \ln\left(\frac{R_{inf}}{((x-x_j)^2+(y-y_j)^2)^{1/2}}\right) + C \qquad (8.13)$$

and

$$\psi = Uy + \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \tan^{-1}\left(\left(\frac{y-y_j}{x-x_j}\right)\right). \qquad (8.14)$$

Equations 8.10 and 8.11 become

$$\frac{dx}{dt} = \frac{KU}{P} + \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \left(\frac{x-x_j}{(x-x_j)^2+(y-y_j)^2}\right) \qquad (8.15)$$

and

$$\frac{dy}{dt} = \sum_{j=1}^{n} \frac{Q_j}{2\pi DK} \left(\frac{y-y_j}{(x-x_j)^2+(y-y_j)^2}\right). \qquad (8.16)$$

Extensions From Previous Work

Transform for gradient rotation--

The uniform flow field assumed in Equations 8.13, 8.14, 8.15, and 8.16 is directed from west to east. In actuality, the uniform flow gradient may come from any direction and should be accounted for in the model. This is accomplished by mathematically rotating the flow field from its assumed position (west to east) to its real position. The x component of flow due to the uniform flow gradient is multiplied by the cosine of the angle of rotation (Θ_r). The y component is multiplied by the sine of the angle of rotation.

Equations 8.13, 8.14, 8.15 and 8.16 become

$$\phi = -U\left(x\cos(\theta_r) + y\sin(\theta_r)_\rho\right) + \sum_{j=1}^{n} \frac{Q_i}{2\pi DK} \ln\left(\frac{R_{nf}}{\left((x-x_i)^2(y-y_i)^2\right)^{1/2}}\right) + C, \qquad (8.17)$$

$$\psi = U\left(y\cos(\theta_r)+x\sin(\theta_r)\right) + \sum_{i=1}^{n} \frac{Q_i}{2\pi DK} \ln\left[\tan^{-1}\left(\frac{y-y_i}{x-x_i}\right)\right], \qquad (8.18)$$

$$\frac{dx}{dt} = \frac{KU}{P}\left[\cos(\theta_r)\right] + \sum_{i=1}^{n} \frac{Q_i}{2\pi DP}\left(\frac{x-x_i}{(x-x_i)^2+(y-y_i)^2}\right), \qquad (8.19)$$

and

$$\frac{dy}{dt} = \frac{KU}{P}\left[\sin(\theta_r)\right] + \sum_{i=1}^{n} \frac{Q_i}{2\pi DP}\left(\frac{y-y_i}{(x-x_i)^2+(y-y_i)^2}\right). \qquad (8.20)$$

The direction of the uniform flow field is determined by an input parameter (refer to input description in program listing). With north defined as 0°, east as 90°, etc., the user can input any direction desired. Figures 8.4a, 8.4b, and 8.4c have identical well and aquifer parameters except for the direction of the uniform flow field.

Figure 8.4a has the flow field originating from the west (270°), behind the injection well towards the pumping well. Nearly all the flow lines emanating from the injection well are intercepted by the pumping well.

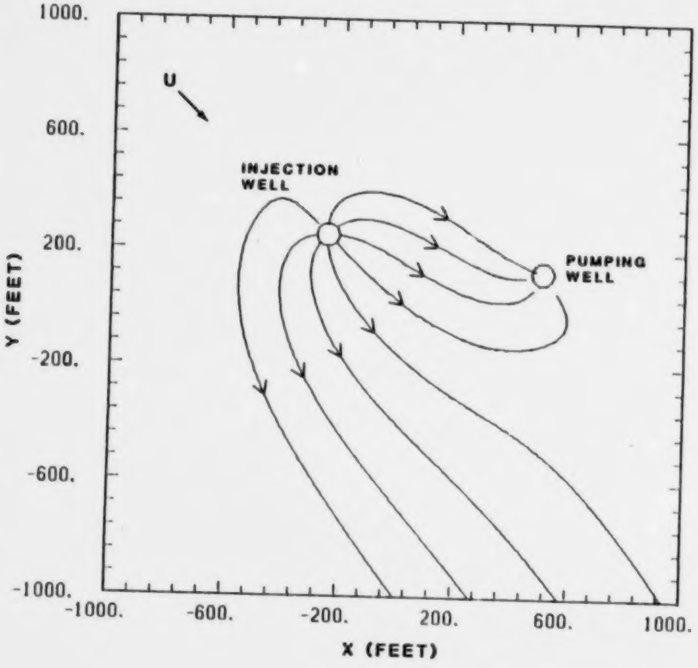

Figure 8.4b Flow lines for dipole well system and a uniform flow direction of 330°

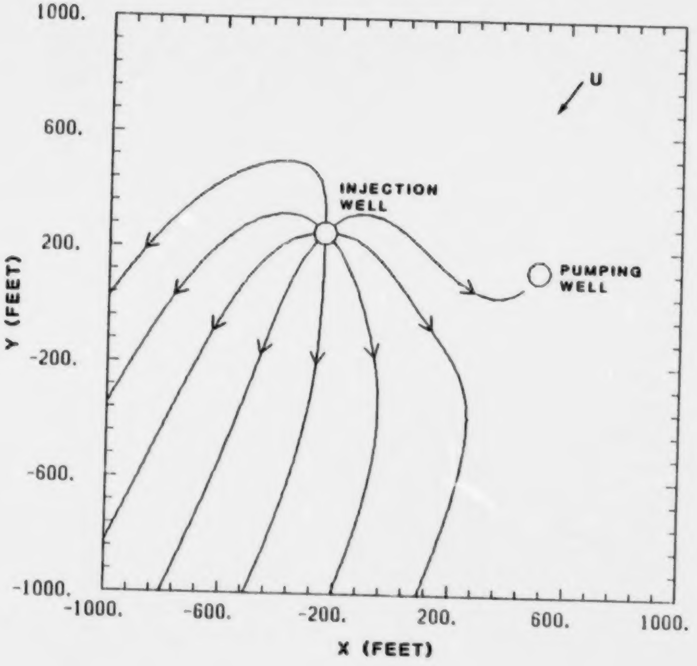

Figure 8.4c Flow lines for dipole well system and a uniform flow direction of 30°

Figure 8.4b shows the flow field originates from the northwest (330°) and demonstrates the degree to which the uniform flow direction can affect the flow lines from an injection well. In this case, only one-half of the well flow from the injection well terminates at the pumping well.

Figure 8.4c demonstrates an unfavorable situation for pumping well interception of injection well fluids. The uniform flow gradient is coming in at an angle (30°) that will subtract from the pumping/injection well gradient. Nearly all injected fluid would flow toward the southwest, away from the pumping well, due to the magnitude and direction of the ambient flow regime.

Piezometric surface--

A piezometric surface is a contour map of the hydraulic head in an aquifer and provides an indication of the directions of groundwater flow. The hydraulic head calculations in this study assume horizontal flow in a confined aquifer which has a hydraulic conductivity much higher than conductivities in the confining beds. The piezometric surface reflects the pressure effects caused by injection and pumping wells as they appear within the uniform flow field. A model generated map of the piezometric surface also facilitates model calibration with field data.

Equation 8.20 can be used to determine the hydraulic head (and thereby the piezometric surface) at any location (x,y) in the aquifer (except where the location (x,y) is a source or sink). POLLUTE evaluates Equation 8.20 for an equally spaced 30 x 30 nodal point matrix and then calls a contouring routine to contour the points into a piezometric surface (equipotential lines). The resulting equipotential lines are everywhere orthogonal to the flow lines calculated by POLLUTE except where the aquifer is anisotropic (Figures 8.5 and 8.6). (The anisotropic capability of the model will be discussed later.) When a piezometric point to be contoured is located at a source or sink, the head value of that point approaches negative infinity. If a point is located within the radius of a well, POLLUTE gives it the value of a point located on the well radius while it maintains its original location. Therefore, when the contouring routine is called by POLLUTE, the contours may cross over inside the well radius (Figure 8.5).

The hydraulic head within a study area at the origin (0,0), without any sources or sinks, is given by C in Equation 8.20. This variable is given an arbitrary value of zero, but can be changed prior to compilation of the program. Any values for C other than zero result in adding that value to all the calculated hydraulic heads.

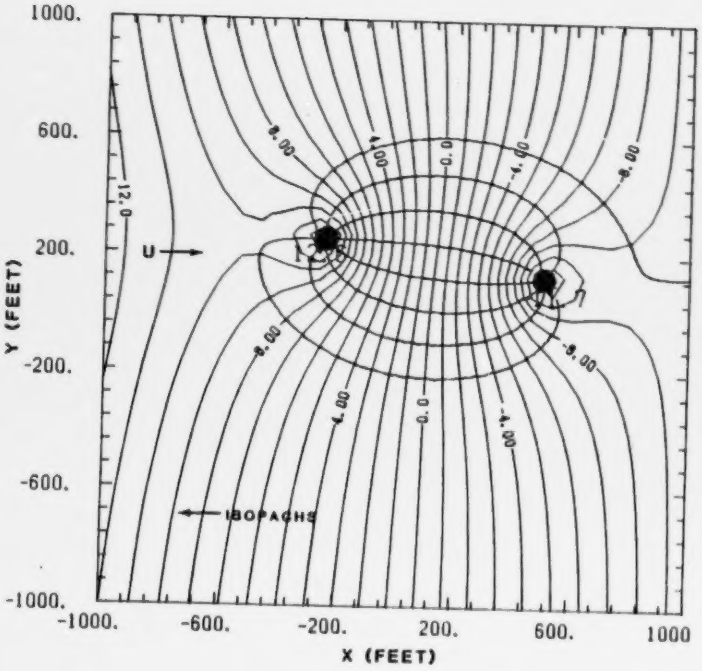

Figure 8.5 Flow lines and equipotential lines (lines of equal head) under isotropic conditions

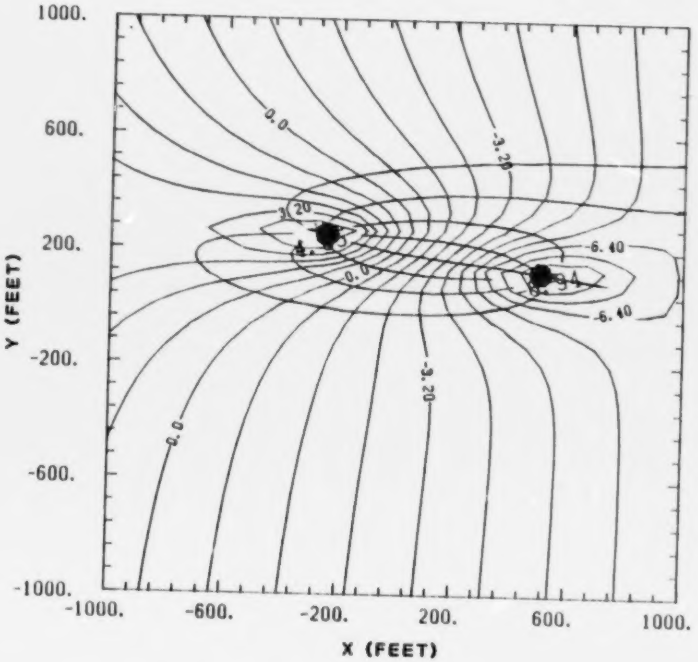

Figure 8.6 Flow lines and equipotential lines under anisotropic conditions

Anisotropy--

An aquifer is considered anisotropic when its hydraulic conductivity is a function of direction. A homogeneous, isotropic aquifer has a constant hydraulic conductivity along any direction. Hydrologic problems involving two-dimensional flow within a homogeneous, anisotropic media can be solved by transforming the anisotropic domain into an isotropic one. Once the problems are solved for the isotropic domain, the solutions are transformed back into the anisotropic domain. If an aquifer is anisotropic in the horizontal plane, it is very important to be able to incorporate this anisotropy in the model that will aid in designing monitoring networks. This is primarily because contaminants do not necessarily flow in the same direction as the gradient in an anisotropic media. Thus if the analyst was depending solely on the gradient direction to determine monitoring well placement, he might miss interception of contaminants resulting from anisotropic conditions.

Conceptually, the anisotropic media is a spatially reduced or expanded isotropic media along a principle axis. If an aquifer is anisotropic along the x axis by a factor of nine (permeability parallel to the x axis is three ($\sqrt{9}$) times the permeability parallel to the y axis), the equivalent isotropic media would have its x axis condensed by a third (expansion or contraction of the media is determined by the square of the relative permeability). For example, two wells within the above anisotropic media, located 18 feet apart along the x axis, would be located 6 feet apart in the corresponding isotropic medium. To determine the transform from the anisotropic to isotropic media for a variable permeability (K(x)), the Darcian velocities of the two systems are equated to each other;

$$\frac{d(-K\ dh)}{dx} = \frac{d(-\bar{K}\ dh)}{d\bar{x}}, \tag{8.21}$$

which becomes

$$K \frac{d^2h}{dx^2} = \bar{K} \frac{d^2h}{d\bar{x}^2}, \tag{8.22}$$

where $\bar{x}$ is the transformed coordinate and K is the secondary hydraulic conductivity.
Solving for $\bar{x}$ yields the transform

$$\bar{x} = \frac{\bar{K}}{K} x . \tag{8.23}$$

POLLUTE can be used with anisotropy in either the x or y direction, as long as the principal directions of anisotropy are in the x and y directions. When the system is anisotropic in x or y, a transform graph is plotted out with the output. This graph displays the transformation from the true coordinate x (or y) to the transformed coordinates $\overline{x}$ (or $\overline{y}$).

If the isotropic aquifer in Figures 8.7a and 8.7b was anisotropic in the x direction by a factor of 9, the transform graph would be plotted with a slope of 1/3 (Figure 8.8a). Figures 8.8b and 8.8c show the flow line and piezometric plot) of the anisotropic aquifer. If the aquifer were anisotropic by a factor of 9, the same transform graph would appear (Figure 8.9a) but the flow line and piezometric plots (Figure 8.9b and 8.9c) would be considerably different. Groundwater flow would preferentially be in the y direction, rather than the x direction.

Boundary Conditions--

The model as presented to this point considers a well (or wells) in an aquifer of infinite areal extent or discontinued beyond the well radius of influence. However, aquifer discontinuities may occur within the radius of influence of a given well and can have a notable effect on the flow regime around that well and in the uniform flow field. The aquifer discontinuities handled by POLLUTE are equipotential surfaces such as lakes or streams, and/or impermeable boundaries such as fault zones. These aquifer discontinuities are considered linear and can be accounted for by the use of image wells.

According to the method of images (Bear, 1972), the flow field beyond the boundary is replaced by a fictitious flow field eliminating the boundary of the real field. The fictitious field consists of image sources and sinks of strengths equal to the corresponding sources and sinks in the real domain. Each image source or sink, and the corresponding real source or sink, lies at equal distances from each other on a vector normal to the boundary.

For an impermeable boundary, a real source has a corresponding image source, and a real sink has a corresponding image sink. Along this boundary, the effect of the real well is doubled by the cumulative effect of its image well.

Equipotential boundaries are treated in a similar manner to those for impermeable boundaries except that a real source has a corresponding image source. Along this boundary, the effect of the real well is negated by the effect of its image well.

To satisfy continuity, impermeable boundaries should be placed parallel to the uniform flow gradient. If they are placed at any other angle, the uniform flow gradient will cause groundwater to pass through the boundary.

Compared with a nonbounded aquifer (Figures 8.10a and 8.10b), Figures 8.11a, 8.11b, 8.12a, and 8.12b show how fluid

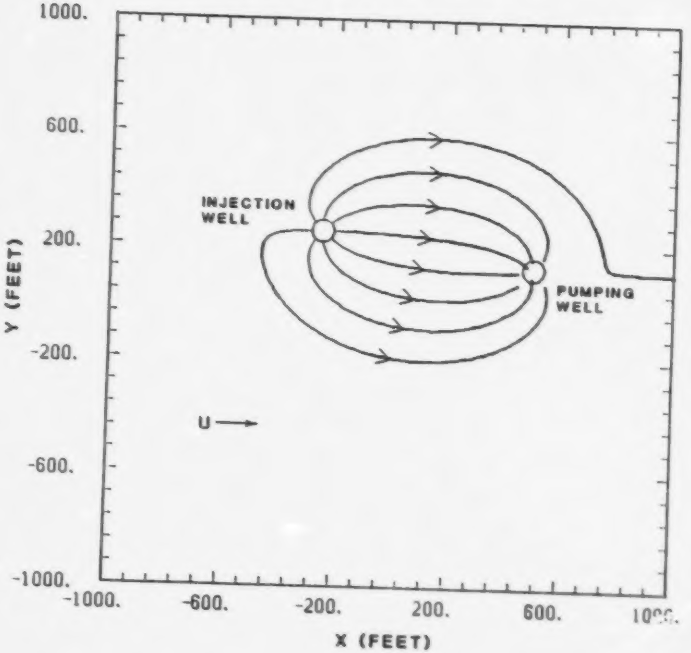
INJECTION WELL
PUMPING WELL
U
Y (FEET)
1000.
600.
200.
-200.
-600.
-1000.
X (FEET)
-1000.
-600.
-200.
200.
600.
1000.

Figure 8.7a Flow lines under isotropic conditions

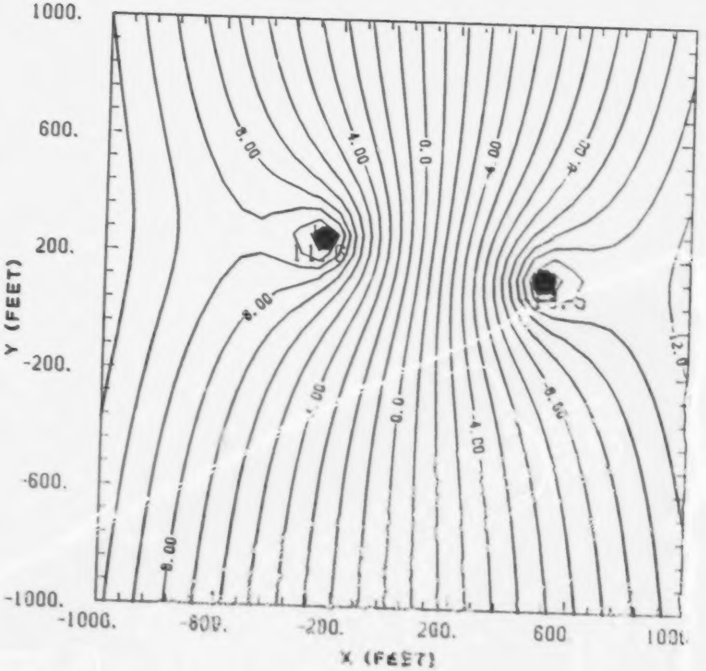

Figure 8.7b Piezometric surface under isotropic conditions

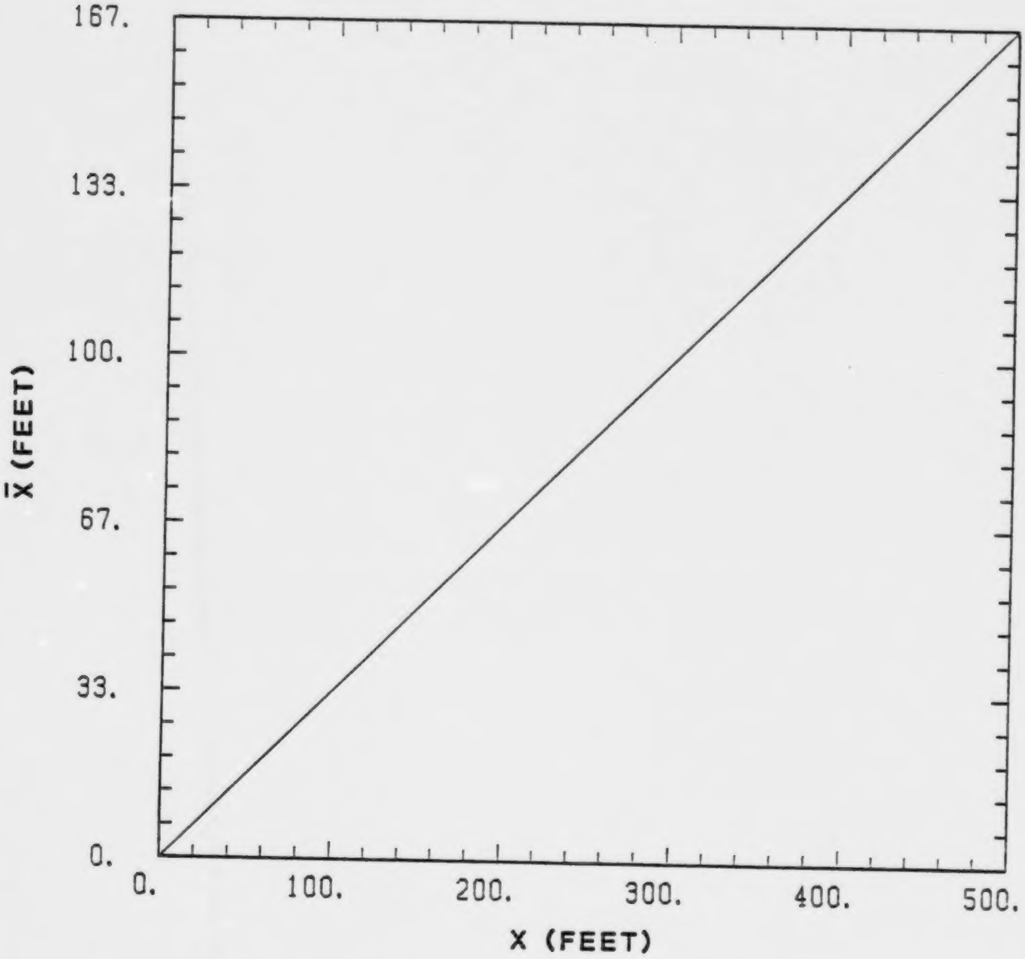

Figure 8.8a Transform for x anisotropy

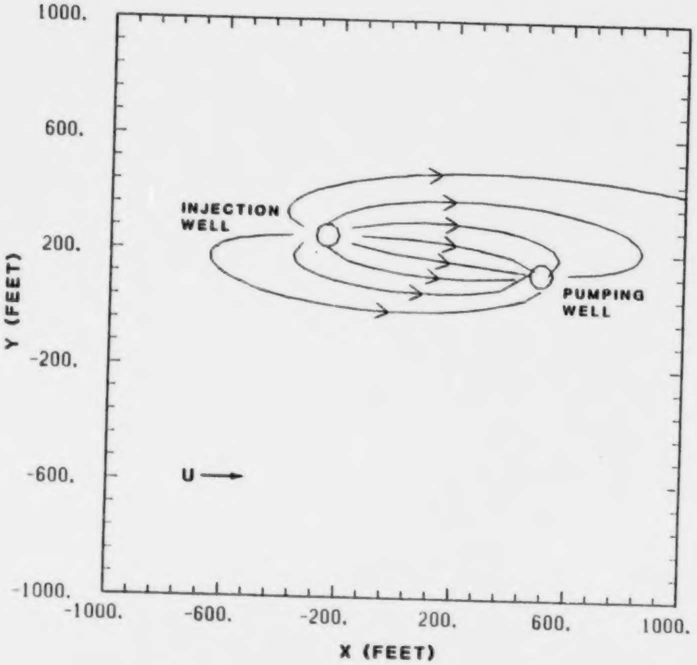

Figure 8.8b Flow lines for constant anisotropy in x

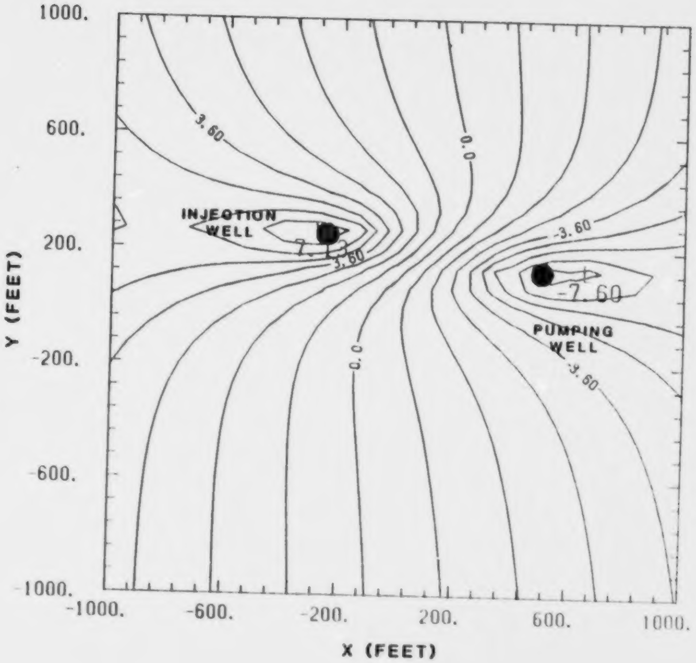

Figure 8.8c Piezometric surface for constant anisotropy in x

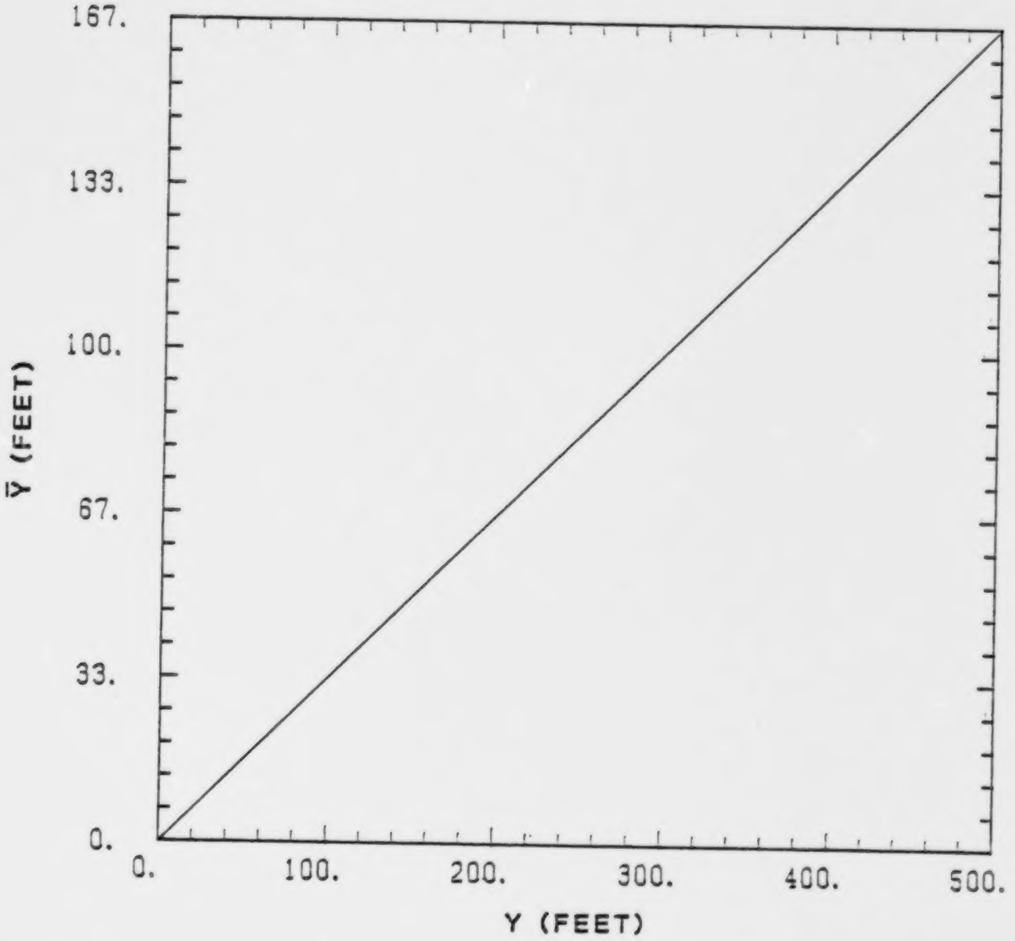

Figure 8.9a Transform for y anisotropy

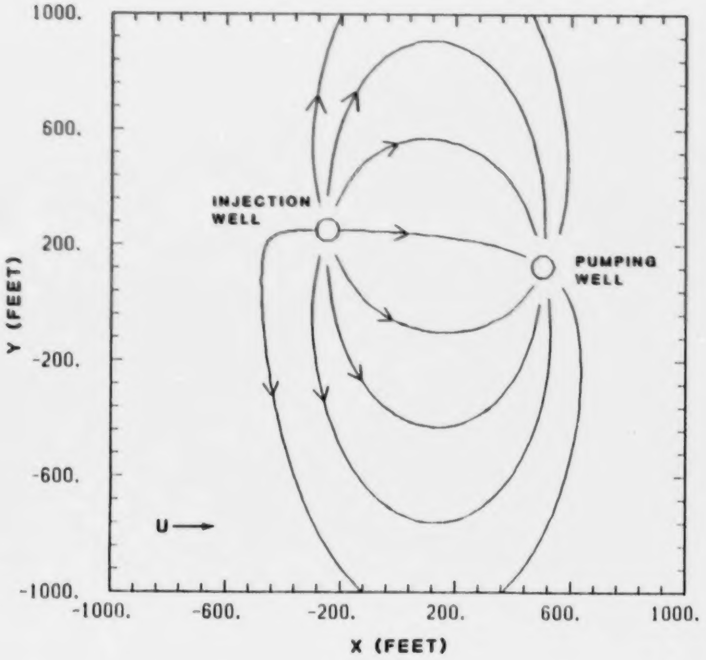

Figure 8.9b Flow lines for constant anisotropy in y

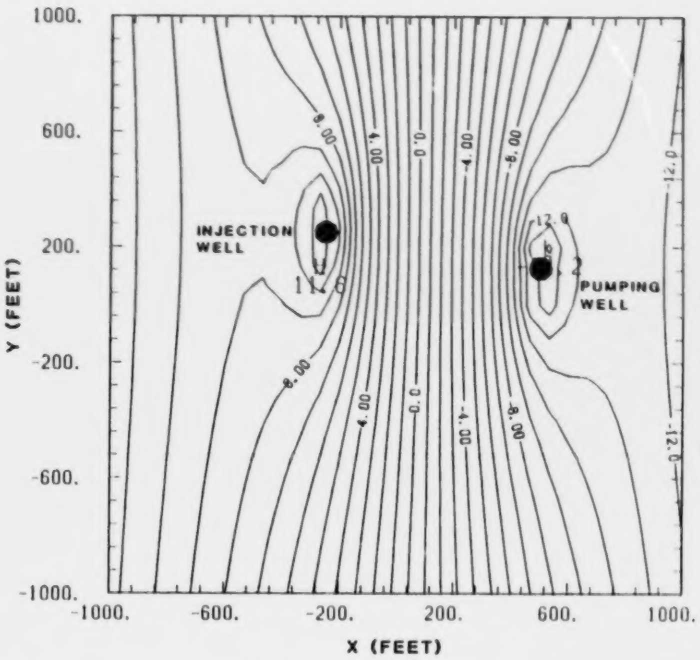

Figure 8.9c Piezometric surface for constant anisotropy in y

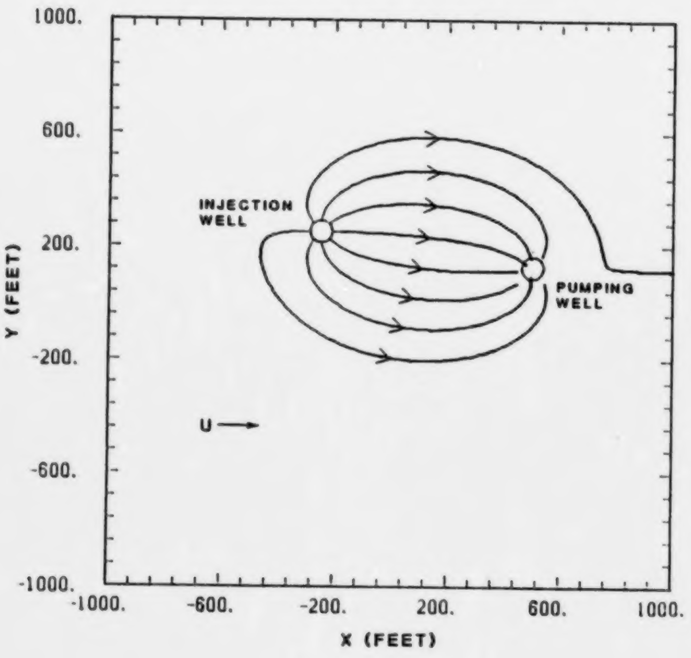

Figure 8.10a Flow lines in an unbounded aquifer

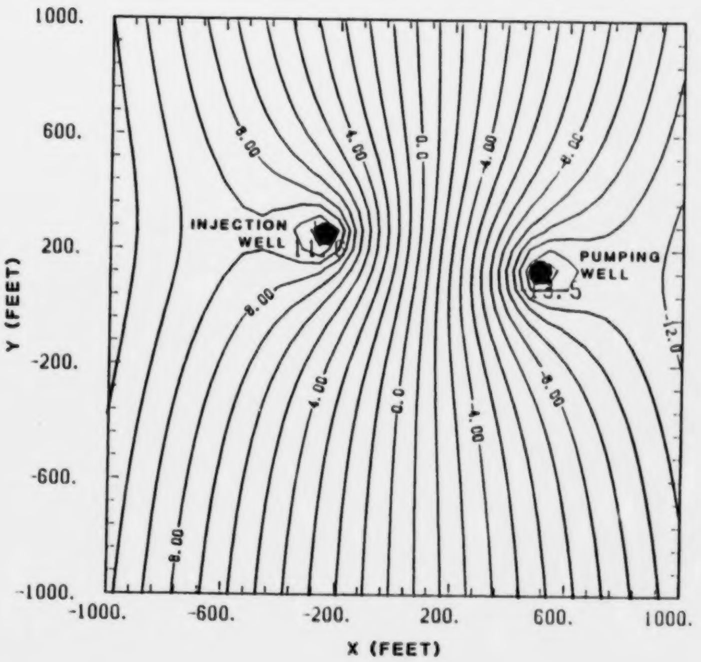

Figure 8.10b Piezometric surface in an unbounded aquifer

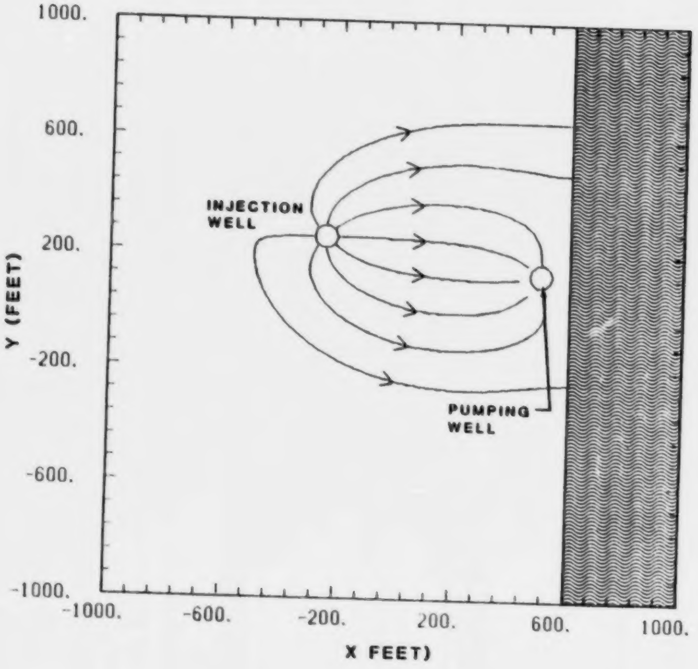

Figure 8.11a Flow lines where equal potential boundary is at x = 600 feet

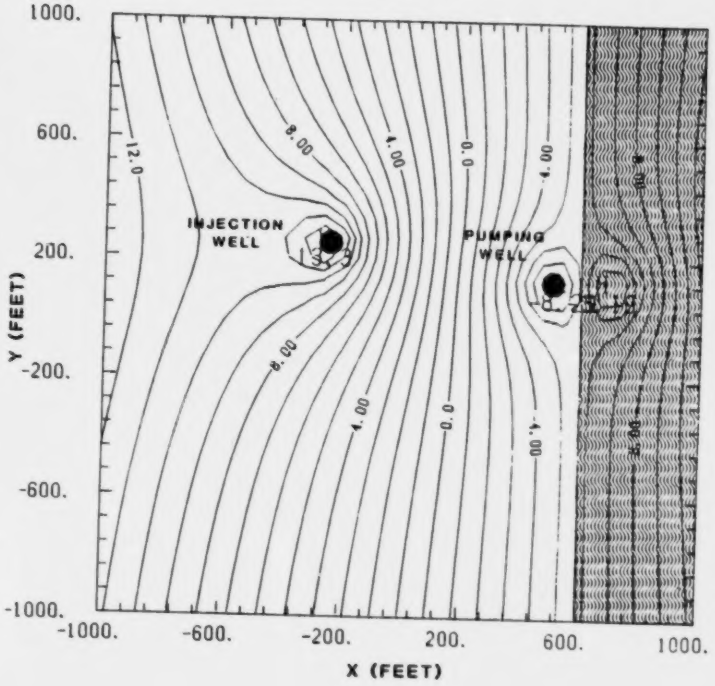

Figure 8.11b Piezometric surface where equal potential boundary is at x = 600 feet

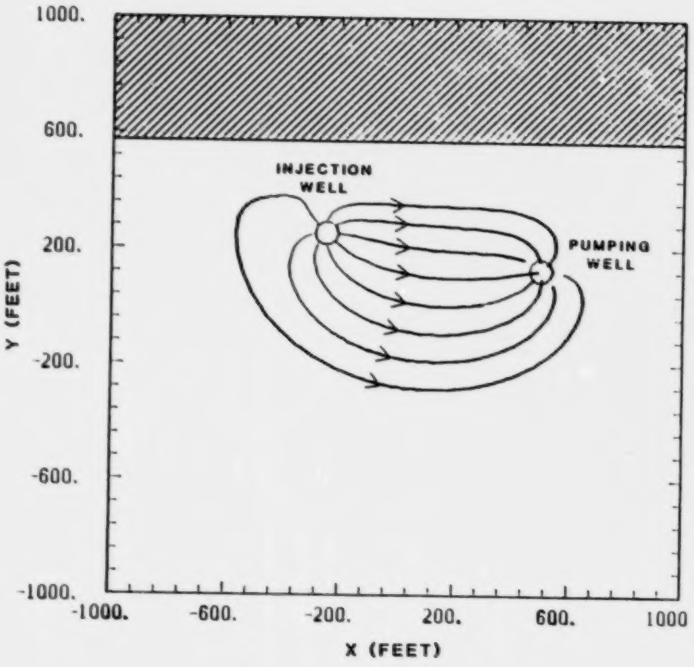
1000.
600.
200.
-200.
-600.
-1000.
Y (FEET)
-1000.
-600.
-200.
200.
600.
1000
X (FEET)
INJECTION WELL
PUMPING WELL

Figure 8.12a Flow lines where impermeable boundary is at y = 400 feet

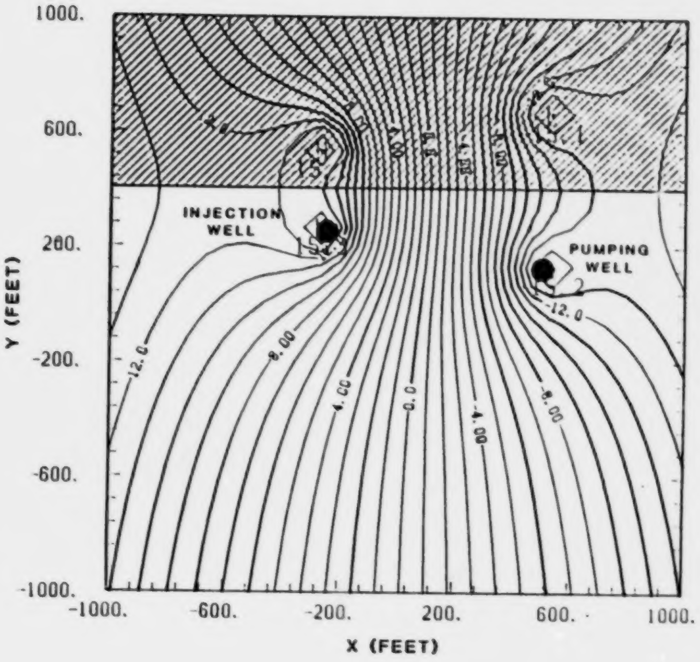

Figure 8.12b Piezometric surface where impermeable boundary is at y = 400 feet

flux and pressure changes may be caused by the presence of equipotential or impermeable boundaries. The image wells do not appear on the flow line maps (Figures 8.11a and 8.12a) but they do appear in the form of high and/or low piezometric zones directly across the boundaries from the real wells (Figures 8.11b and 8.12b). These zones are not real and should be ignored.

Equipotential boundaries tend to minimize the effects wells have in an aquifer. An injection well located near an equal potential boundary will discharge most of its solute into the boundary as opposed to the rest of the aquifer. A similar effect occurs with a pumping well since the recharge boundary acts as a source area for that well. Figures 8.11a and 8.11b show that with an equal potential boundary (i.e. a lake or stream) located at x = 600 feet, flow lines that normally would terminate at the pumping well, terminate at the boundary. This is due to the effect of an image injection well located just across the boundary from the pumping well.

Impermeable boundaries tend to magnify the effects of wells in an aquifer. The discharge of an injection well located near an impermeable boundary will be repelled away from the boundary. Similarly, a pumping well will draw all its discharge from the aquifer region opposite the boundary. Figures 8.12a and 8.12b show that with an impermeable boundary located at y = 400 feet, flow lines are flattened and deflected away from the boundary. These deflections are caused by the image wells located across the boundary.

Well Flow Distribution

Nelson (1978b) showed how his model can be used to give a distribution of the mix of ambient and polluted waters as a function of time at a well. The mix of ambient and contaminated waters is the fraction of solute from a specific injection well being discharged compared to the total fluid discharge of the pumping well. This distribution can be considered a breakthrough curve for the contaminant at that well. This curve may be important in determining how long a contaminated well should stay in operation. Again, dispersion is ignored. If dispersion is considered, the well flow distribution would show solute interception earlier than it does.

The well flow distribution is calculated from the stream function (Equation 8.9), where the discharge represented by each well flow line is determined. Nelson (1978b) calculated the distribution at only one well to show the utility of such a distribution. In this study, the calculations have been expanded to yield a distribution for any pumping well that intercepts two or more flow lines from the same injection well. The total discharge of the pumping well may contain solute from more than one injection well, in which case multiple distributions would be output.

POLLUTE employs a polynomial regression routine to give a polynomial function for the well flow distribution. This enables the user to obtain an approximation of the ambient fluid/pollutant mix for a given pumping well at any time during pollutant interception. However, comparison of the graphical output from the well flow distribution and the polynomial regression (Figures 8.13a and 8.13b) indicates that the regression used is not ideal and is at best an approximation. As an example, at 1.74 years the well flow distribution (Figure 8.13a) yields a value for Q_i/Q_0 of 0.83 where the polynomial regression (Figure 8.13b) yields a value of 0.79. The user is advised to compare the graphical ouktputs before relying on the polynomial. Since the regression relies on the data points produced by POLLUTE, the more flow lines used by POLLUTE, the more data points for the regression, the more accurate the polynomial approximation of the breakthrough curve. However, the breakthrough curve is an approximation to begin with (dispersion would alter it and even then the dispersion coefficients are only approximations) and thus implies that a more exact polynomial approximation of the breakthrough curve may not be warranted.

Numerical Formulation: The Runge-Kutta Method

The Runge-Kutta method is a numerical technique used to solve first order ordinary differential equations. It is a single step and self-starting algorithm. That is, it calculates one step at a time and requires no previous step calculations. The fourth order Runge-Kutta method retains the same accuracy as a fourth power Taylor series.

POLLUTE, using the Runge-Kutta method, numerically solves Equations 8.19 and 8.20. The position at the next time step for a discrete fluid "particle" is thereby determined. The end result of the numerical computations is a loci of points (a point for each time step) delineating a flow path for that particle of fluid. The isochronal distribution produced by POLLUTE indicates the location of the fluid particle at every twentieth time step. POLLUTE plots the flow path for a particle of fluid as a line, and the isochronal distribution as a series of points. The fourth order Runge-Kutta scheme for two coupled expressions:

$$\frac{dX}{dt} = f(X,Y) \qquad \text{and} \qquad \frac{dY}{dt} = g(X,Y),$$

is to be solved simultaneously.

The equations are as follows:

$$X_{i+1} = X_i + \frac{h}{6h}\left(K_1+2K_2+2K_3+K_4\right), \qquad (8.24)$$

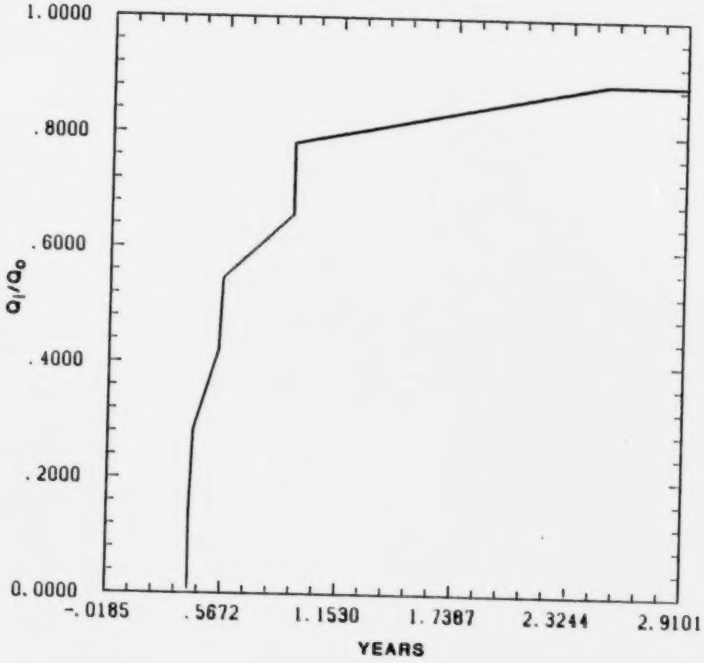

Figure 8.13a Well flow distribution for injected fluid arriving at pumping well

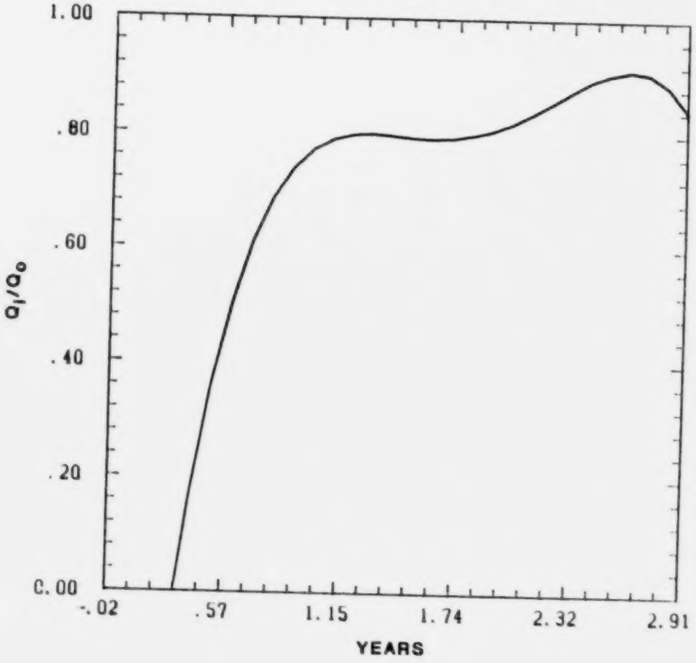

Figure 8.13b Polynomial regression of well flow distribution

$$Y_{i+1} = Y_i + \frac{h}{6}\left(C_1+2C_2+2C_3+C_4\right). \qquad (8.25)$$

where

h = incremental step size,

$$K_1 = f\left(X_i, Y_i\right),$$

$$C_1 = g\left(X_i, Y_i\right),$$

$$K_2 = f\left(X_i + \frac{h}{2} K_1, Y_i + \frac{h}{2} C_1\right),$$

$$C_2 = f\left(X_i + \frac{h}{2} K_1, Y_i + \frac{h}{2} C_i\right),$$

$$K_3 = f\left(X_i + \frac{h}{2} K_2, Y_i + \frac{h}{2} C_2\right),$$

$$C_3 = g\left(X_i + \frac{h}{2} K_2, Y_i + \frac{h}{2} C_2\right),$$

$$K_4 = f\left(X_i+hK_3, Y_i+hC_3\right),$$

$$C_4 = g\left(X_i+hK_3, Y_i+hC_3\right).$$

For a detailed description of the numerical errors that may be encountered with this numerical method, see Ornstein (1982).

MODEL VERIFICATION

Analytical Comparisons

Analytical solutions and another numerical model (developed by Konikow and Bredehoeft, 1978) were used to determine the accuracy of the numerical scheme used in this program. Four analytical solutions were employed for simple well configuration problems. These were used as a check against the flow line and isochronal plots produced by POLLUTE. The numerical model was used to check the extent of a contaminant plume from the output produced by POLLUTE for a specified well field scenario.

The analytical solutions and comparisons were straightforward. The analytical solutions agreed with the numerical solutions in all four cases to a high degree of accuracy. The four solutions and their comparisons can be found in Ornstein (1982). The numerical solution comparison will be discused here because there are some interesting observations regarding the difference between results from POLLUTE, an advective model, and an advective-dispersion model set up to solve the same problem.

Numerical Comparison

One method to test the accuracy of POLLUTE for situations other than the simplistic ones that can be analyzed analytically is to compare it to another model which has a numerical scheme different from the Runge-Kutta method used in POLLUTE. The extent and shape of an injected plume at a specified time, and the concentration of an injected contaminant at a pumping well as the concentration at that well varies with time, can be compared for the two models.

The numerical model used for this check was a groundwater solute transport model (Konikow and Bredehoeft, 1978), hereafter referred to as SOLUTE. This model was chosen because it is a recognized model that produces output which can be compared to that from POLLUTE. SOLUTE solves the solute transport equation (Equation 8.3) by the Method Of Characteristics, which is a particle tracking finite different scheme. Hydrodynamic dispersion coefficients for both longitudinal and transverse dispersion are input parameters in SOLUTE. These coefficients may be given a value to simulate dispersion, or may be left as zero for strictly advective flow.

A scenario was created for both POLLUTE and SOLUTE consisting of a pumping and an injection well within a uniform flow field. The pumping well was located southeast of the injection well, and the uniform flow field was from the north (Figure 8.14). The study area was bounded by equal head boundaries on the north and south, and impermeable boundaries on the east and west.

The intersection of the equal head and impermeable boundaries at the four corners of the study area created a problem for POLLUTE. POLLUTE addresses each boundary by projecting an image well across the boundary for each well. However, to be more accurate, each image well should project its own image well back across each boundary. And each of those image wells should have their own image wells, and so on ad infinitum. The error caused by ignoring the additional image wells is negligible except where a source or sink is located near two or more boundaries. The results of such an error can be seen in Figure 8.15, where POLLUTE apparently has several flow lines traversing across the impermeable boundary toward the west. Figure 8.15 is similar to the comparison scenario described above except that the boundaries are closer to the wells. Mass will be erroneously removed from the system by the image well boundary error intrinsic to POLLUTE and may be reflected in the model comparison.

Contaminant concentration data for all grid elements and total contaminant mass data for the mass leaving the groundwater system through the pumping well, and through the equal head boundaries were determined with SOLUTE. These output data were

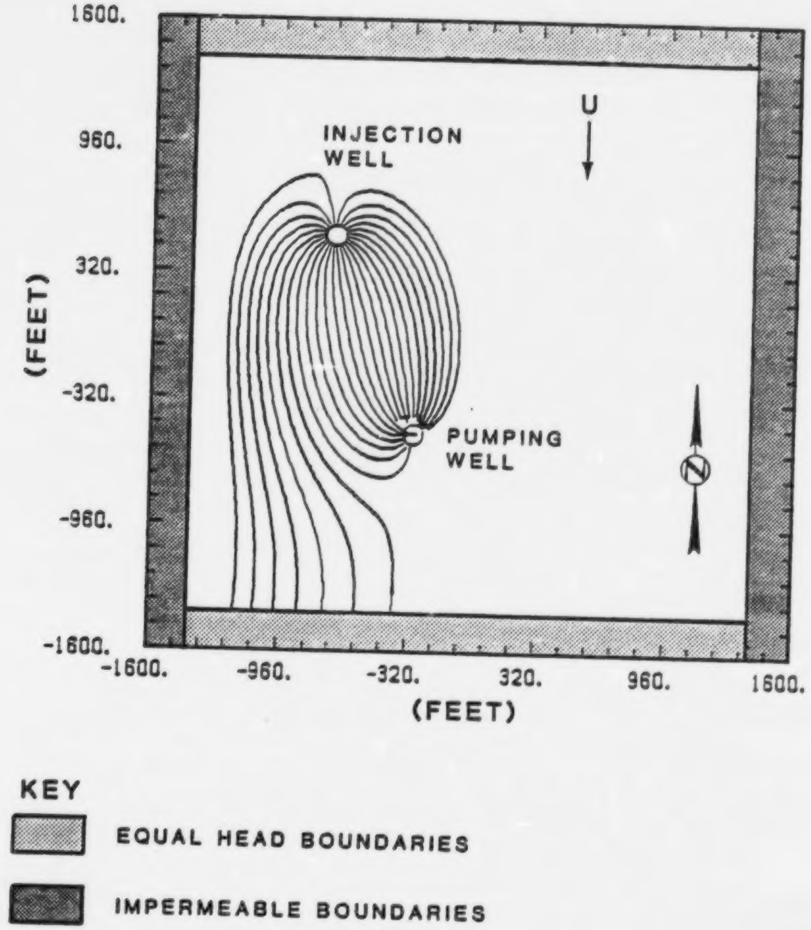
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Figure 8.14 Comparison scenario for POLLUTE vs. SOLUTE

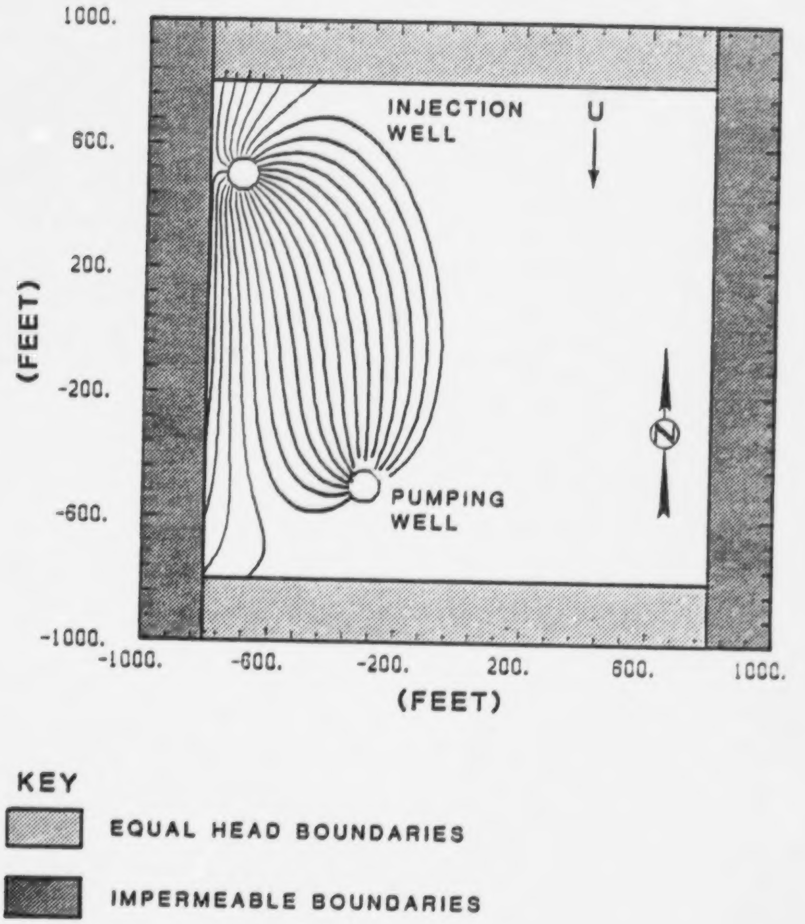

Figure 8.15 POLLUTE showing flow through an impermeable boundary

updated at regular iteration intervals. Output from POLLUTE consisted of flow line maps, isochron maps, and well flow distribution graphs with their corresponding polynomial regressions. Comparison of the extent of the contaminant plume after five years was achieved using isochron and flow line maps from POLLUTE, and with the element concentrations given by SOLUTE. Comparison of the amount of contaminant interception at the pumping well was made using the well flow polynomial regression from POLLUTE and the contaminant mass loss through a pumping well data output from SOLUTE. The polynomial regression from POLLUTE was integrated and multiplied by the pumping well discharge to bring it into a form comparable with the SOLUTE output. Initially, the polynomial regression was of the form

$$Q_i/Q_0 = A + B1(t) + B2\ t^2 + B3\ t^3 + B4\ t^4 \qquad (8.26)$$

where Q_i is the contaminant interception rate, Q_0 is the pumping discharge rate, and t is the time in years. After integration, Equation 8.26 became

$$Q_{icum} = A\ t + B\ \frac{t^2}{2} + B2\ \frac{t^3}{3} + B3\ \frac{t^4}{4} + B4\ \frac{t^5}{5}\quad Q_o \qquad (8.27)$$

evaluated from the time of initial contaminant interception to the time specified. Q_{icum} is the total amount of contaminant intercepted at the pumping well during the chosen time range.

The comparison scenario previously described was run twice for the two models. The first run considered strictly advective contaminant flux and set the dispersion coefficients equal to zero in SOLUTE. The second run incorporated arbitrary longitudinal and traverse dispersion (D_L and D_T) values of 100 feet and 30 feet, respectively. These values were arbitrarily chosen by the analyst based on the scale of the study area being modeled.

Comparison between well uptake values for the two models are shown in Table 8.1. The values for Q_{icum} were calculated with Equation 8.27, evaluated beginning at 1.06 years. However, because the polynomial regression (Equation 8.26) is an approximation for Q_i/Q_o values between 0.59 and 3.99 years (Figures 8.16 and 8.17), the polynomial regression and Equation 8.26 are not valid past 3.99 years. Beyond 3.99 years, Q_i/Q_o is constant (0.75 extrapolated from Figure 8.16). Q_{icum} can then be calculated by summing equation 8.26, evaluated from 1.06 to 3.99 years, and 0.75(t), evaluated from 3.99 years to the year specified. Comparison of POLLUTE values to the nondispersive SOLUTE values shows a substantial discrepancy but a very good overall correlation between the two data sets. The initial discrepancy may be due to the image well boundary errors described

TABLE 8.1

Comparison between SOLUTE and POLLUTE for Contaminant Mass Intercepted at a Pumping Well

Years	SOLUTE (Dispersion)	SOLUTE (No Dispersion)	POLLUTE[a]	% Dev. 1[b]	% Dev. 2[c]
0.53	5.32 (10^4)[d]	--	--	--	--
1.06	9.35 (10^5)	--	--	--	--
1.60	3.67 (10^6)	3.30 (10^6)[d]	2.48 (10^6)[d]	33	48
2.13	7.58 "	7.85 "	6.95 "	13	9
2.66	1.21 (10^7)	1.29 (10^7)	1.19 (10^7)	8	2
3.19	1.69 "	1.81 "	1.73 "	5	-2
3.72	2.18 "	2.33 "	2.32 "	0	-6
4.26	2.68 "	2.86 "	2.93 "	-2	-9
4.79	3.28 "	3.39 "	3.52 "	-4	-10
5.00	3.38 "	3.60 "	3.76 "	-4	-10

a) POLLUTE values calculated from equation 4.20 where
A = -3.4297, B1 = 5.9410, B2 = -3.2842, B3 = 0.8042m and B4 = -0.0724

b) % Dev. 1 is the percentage SOLUTE (no dispersion) deviates from POLLUTE.

c) % Dev. 2 is the percentage SOLUTE (dispersion) deviates from POLLUTE.

d) Units are in cubic feet of pure contaminant.

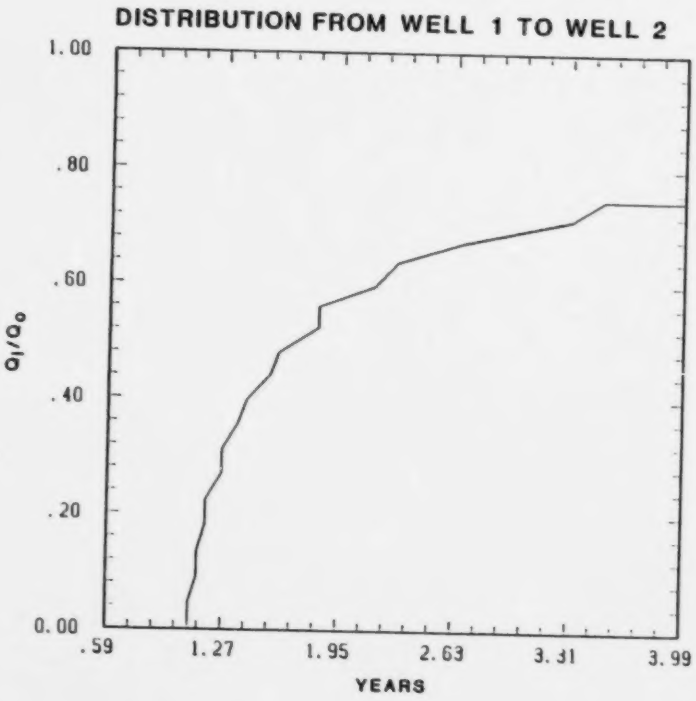

Figure 8.16 Well flow distribution

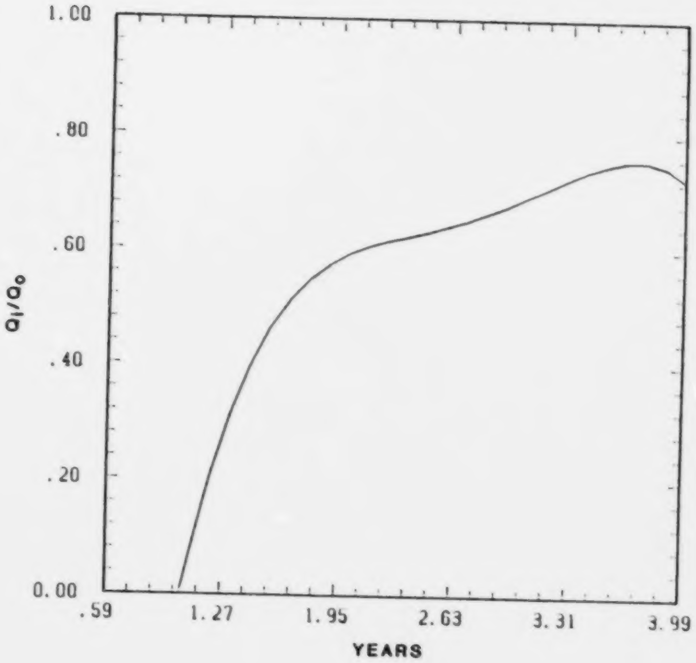

Figure 8.17 Polynomial approximation for well flow distribution

previously, or due to the inexact polynomial approximation of the well flow distribution (Figure 8.17). However, initial contaminant interception started at approximately the same time.

When SOLUTE was used with a dispersive contaminant, pumping well interception started much earlier than the POLLUTE (and SOLUTE) nondispersive contaminant. The dispersive contaminant was being intercepted in greater quantities than the nondispersive contaminant for approximately the first three years. Beyond three years, the cumulative amount of dispersive contaminant was less than that of the nondispersive contaminant. As expected, POLLUTE more closely approximated the SOLUTE nondispersive contaminant than it did the SOLUTE dispersive contaminant.

A comparison was also made between the extent of the POLLUTE five year contaminant plume and the SOLUTE five-year plumes. Figure 8.18 shows the superposition of the nondispersive SOLUTE contaminant plume over the POLLUTE contaminant plume and flow line map. The apparent dispersion of the SOLUTE plume does not result from hydrodynamic dispersion, but by the contaminant plume not covering an entire element area, giving that element a concentration of less than 100 percent. The POLLUTE plume, similar in shape to the SOLUTE plume, is shifted slightly northward of the SOLUTE plume which may be due to the image well boundary problem referred to earlier.

Figure 8.19 shows the SOLUTE dispersive plume superimposed over the POLLUTE plume. The dispersive contaminant plume extends well beyond the POLLUTE plume, but in lower concentrations. The 50 percent isoconcentration line of the dispersed contaminant is closely approximated by the non-dispersed contaminant plume generated by POLLUTE.

In summary, comparison between output from POLLUTE and SOLUTE showed good correlation for interception of a nondispersive contaminant at a pumping well. Comparison of plume extent for the two models showed that POLLUTE closely approximated the 50 percent isoconcentration line of the dispersed SOLUTE plume, while roughly approximating the non-dispersed SOLUTE plume.

SOLUTE may be more versatile than POLLUTE since it can be used to model aquifers containing internal boundaries (i.e., impermeable obstacles). However, POLLUTE yields different information from SOLUTE, which may prove more useful for a given situation. POLLUTE shows flow paths for both ambient and injected ground waters whereas SOLUTE yields concentration values for each element. POLLUTE would therefore be more valuable in determining the potential flow path of a contaminant. POLLUTE can also show contaminant mass uptake at each pumping well in a multiple well system, whereas SOLUTE does not differentiate between pumping wells. This more specific information (from POLLUTE) is neces-

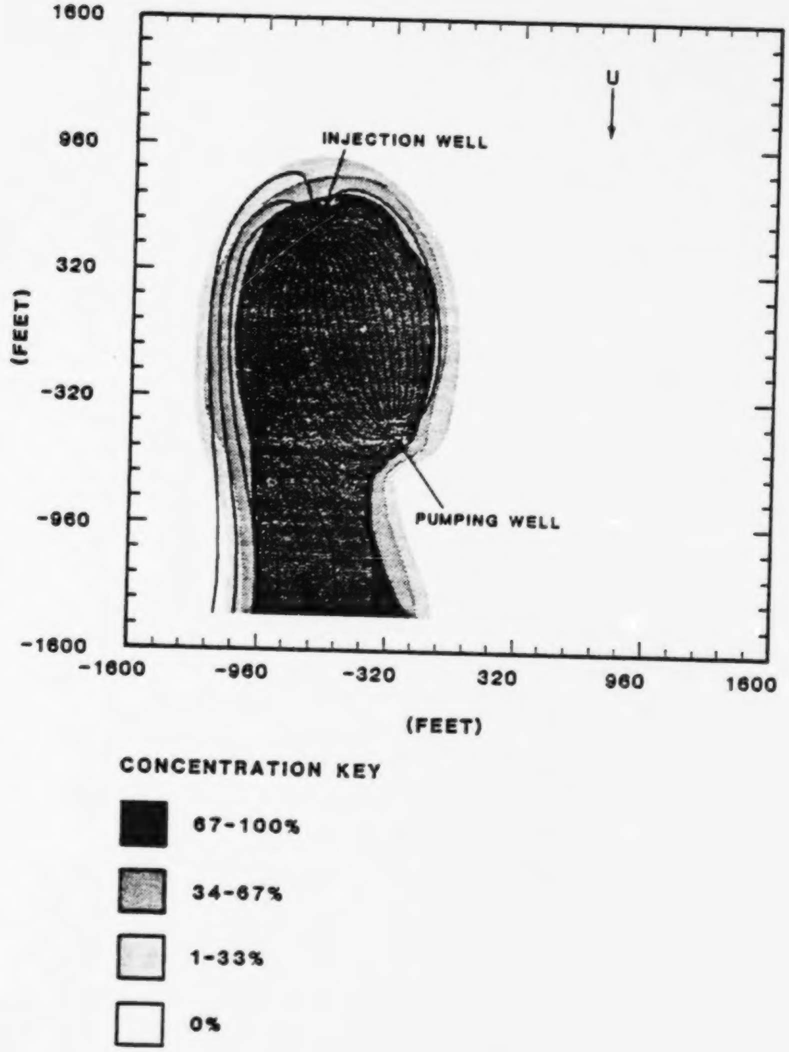

Figure 8.18 Superposition of SOLUTE (nondispersive) plume over POLLUTE plume

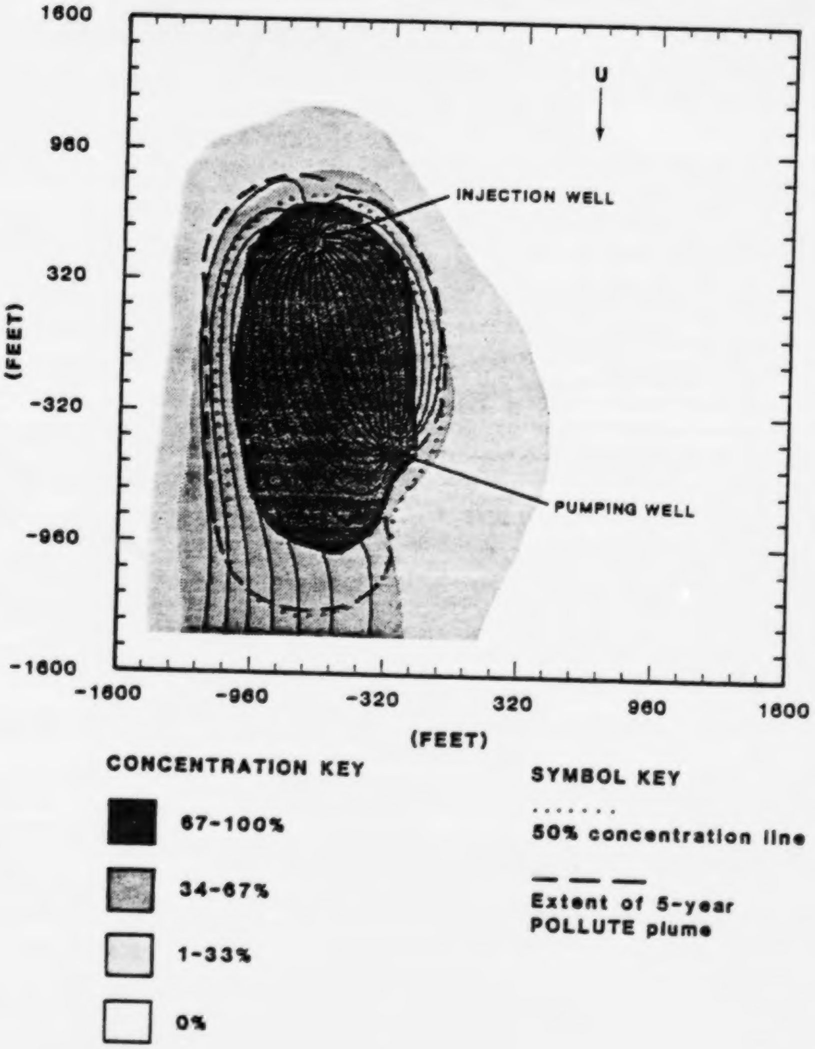

Figure 8.19 Superposition of SOLUTE (nondispersive) plume over POLLUTE plume

sary in determining the well(s) where the contaminant concentration has exceeded set standards. The computer time used during execution of the two models in the previous example (Figure 8.18) showed that the running time of POLLUTE was approximately an order of magnitude faster than that of SOLUTE (35 seconds compared to 246 seconds).

The comparison between SOLUTE (dispersive) and POLLUTE showed the POLLUTE first underestimated the amount of contaminant intercepted at the pumping well, and then overestimated the amount of contaminant being intercepted. The greater the dispersion, the greater the under/over estimate of contaminant interception. Therefore, POLLUTE would yield a conservative estimate (i.e., predict greater interception than actually occurs and thereby leaving a safety margin) in the steady state condition.

SUMMARY AND CONCLUSIONS

Groundwater Flow Simulation

The computer model POLLUTE contains many simplifying assumption which must be taken into consideration. The user should be aware of these assumptions, apply the model to appropriate situations and use the model with caution for situations that deviate from the model assumptions.

The basic simplifying assumptions are:

- The fluid in the aquifer is noncompressible.
- The aquifer is noncompressible.
- The aquifer is a confined aquifer with a uniform thickness. If the aquifer is unconfined, the source/sink term in Equation 8.12 would be

$$\frac{Q_i}{2\pi K} \ln \left(\frac{R_{inf}}{\left((X-X_i)^2 + (y-y_i)^2 \right)^{1/2}} \right)^{1/2}$$

which may be directly derived from Darcy's Law. This term can be differentiated with respect to x and y, and substituted into Equations 8.14 and 8.15 to yield an algorithm for unconfined flow. However, if fluctuations in head are small compared to the aquifer thickness, the algorithm presently used in POLLUTE (which assumes a confined aquifer) can be used for unconfined flow with a minimal amount of error, as per the Dupuit Assumption (which assumes strictly horizontal flow).

- The aquifer has an infinite areal extent except where an image well boundary is placed.
- The aquifer is homogeneous.
- The groundwater regime is under steady state conditions.

- All fluids involved (ambient groundwater and contaminants) have the same density.
- Contaminants are conservative. Where adsorption is known to occur, a lag factor can be used to multiply the arrival time output which would simulate the adsorption.
- The contaminant is assumed to be nondispersive.

In reality all contaminants are dispersive to some extent and the arrival values that POLLUTE yields can be considered the 50 percent point along the contaminant's breakthrough curve. Dispersion will cause some contaminants to arrive earlier than the 50 percent concentration point would indicate.

- The ambient flow gradient is uniform in slope and does not vary in direction.
- All wells are fully penetrating.
- All flow is in a two-dimensional plane.

For this model, strictly horizontal flow was assumed.

The location distribution, coupled with the isochron distribution given by POLLUTE, enables the user to locate a contaminant plume at a given time. By setting up different scenarios, the user can decide which scenario will hasten or retard contaminant flow. Since these distributions are subject to many assumptions (see previous section), contaminant location(s) may not be exact, but should offer a good approximation depending upon the validity of the assumptions. Even with a model that doesn't have simplifying assumptions, the solution normally cannot be considered to be exact because it is very difficult to have a complete understanding of localized and regional aquifer heterogeneities.

The well flow distribution enables the user to determine under a given scenario which well will be contaminated, how much contaminant will be intercepted, and how long it will take for the well to become contaminated.

The graphical representation of flow lines allows the analyst to visualize the flow system in such a way that the placement of monitoring wells for interception of possible leaks from the geothermal system can be easily optimized.

POLLUTE is an easy-to-use efficient model which can simulate most well field situations. For an initial study where there is limited information on the regional hydrogeology, POLLUTE can serve as an ideal model. If more detailed information on contaminant distribution is necessary, and if the hydrogeology is well defined, a finite element or finite difference solute transport model that solves the advective-dispersion equation may be more appropriate.

Summary

POLLUTE is an expanded and revised version of the groundwater flow model developed by Nelson (1978b). Where Nelson's model was limited to an isotropic aquifer of infinite areal extent, POLLUTE can be applied to an anisotropic aquifer which is bounded by impermeable and/or equal potential boundaries. The aquifer anisotropy handled by POLLUTE may be along the x or y-axis. Where Nelson's model assumed a uniform flow field parallel to the x-axis (west to east), POLLUTE makes no such assumption and may include a uniform flow field along any orientation. Other modifications to Nelson's model include well flow distributions for flow into all pumping wells, polynomial approximation of well flow distributions, and simplification of Nelson's algorithm. These revisions have been designed primarily for situations that tend to prevail in geothermal areas in the Great Basin area of Nevada and Utah.

POLLUTE is applicable to a wide range of groundwater contaminant problems. It was used as part of a Department of Energy study to map the potential flow paths of tritium in the groundwater around Tatum Dome, Mississippi (Fenske and Humphrey, 1980), and also used to predict potential well field contamination due to well casing rupture of a planned geothermal injection well in the Raft River KGRA, Idaho. It may also be used in the delineation and interception of a contaminant plume, whether the plume originates from a well or a lagoon.

Both analytical and numerical solutions to various groundwater problems were made and compared to POLLUTE. The analytical solutions solved determined the lateral extent of an injected plume, the travel time between an injection and pumping well, and the location of a stagnation point caused by an injection well within a uniform flow field. The numerical comparison was between output from POLLUTE and output from a groundwater solute transport model that solves the advective-dispersion equation. A scenario was created where a contaminant was tracked between an injection well and a pumping well. The model comparisons included the size and extent of the injected plume, and contaminant intake at the pumping well. In all cases, the analytical and numerical comparisons compared favorably with POLLUTE.

Future Considerations

As in the case with all computer models, no model can ever be considered "finished". There is usually ample room for refinements in the acccuracy of the solution technique, in the diversity of potential uses, and in the manipulation of the output data.

Since most aquifers are not homogeneous, a transform technique needs to be developed to transform a nonhomogenous system into a homogeneous one and hence, increase its credibility in aquifer simulation. The transform should require little computational time and a minimal amount of computer memory in order for POLLUTE to remain a viable alternative to existing FEM and FDM groundwater models.

A leaky aquifer term should also be considered for the many cases where substantial flux occurs across confining aquifer beds. This could be accomplished by decreasing the magnitude of well discharge/recharge by a function of the well strength (pumping/injection rate), confining layer thickness, head differential above and below the confining layer, and hydraulic conductivity of the confining layer.

Similarly, multiple aquifer systems may present a need for further modifications since POLLUTE assumes a single aquifer. This may be accomplished by solving for individual local aquifers, or by assuming a single massive aquifer.

Phreatic aquifers may be approximated by assuming a confined aquifer if head variations are small compared to the thickness of the saturated zone. Otherwise, an alternative algorithm should be employed which accounts for the unconfined aquifer.

It seems apparent that POLLUTE should reflect the delaying effects adsorption may have on a contaminant. Many groundwater contaminants have a tendency to adsorb, or chemically bond, to the aquifer matrix. The effect adsorption has on contaminant movement is to slow down the flow rate of the contaminant with respect to the ambient ground-water. An example of the effect adsorption has on contaminant flow rate has been demonstrated in a study (Higgins, 1959) where the flux of Cs^{137} was four orders of magnitude slower than the flux of the ambient groundwater. Incorporating adsorption into POLLUTE can be accomplished by introducing a lag coefficient which would be a function of the amount of adsorption occurring. The lag coefficient would then be multipled by the arrival times produced by POLLUTE to yield true arrival times of the adsorbed contaminant.

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SECTION 9

GEOCHEMICAL REACTION MODELING

INTRODUCTION

The chemical composition of a geothermal water may be considered to reflect its equilibration to its associated reservoir environment, including temperature, pressure, and host rock mineral assemblage. This is the primary assumption involved in estimating reservoir temperatures by means of chemical geothermometers (Ellis and Mahon, 1977). It is unlikely that a geothermal water will be in equilibrium with its surroundings after temperature and/or pressure declines during energy production or losses to shallower, nonthermal environments.

The chemical disequilibrium resulting from such stresses implies a tendency for the fluid to re-equilibrate to the new conditions by undergoing chemical changes. If remote chemical monitoring for incipient geothermal intrusion into local aquifers is to be considered, then the nature of these potential changes must be understood. This would allow for more intelligent selection of those chemical characteristics which are most diagnostic of intruded geothermal water, eliminating those which may be misleading as a result of chemical alteration processes.

Three steps are needed toward gaining this understanding. They are: 1) selection of essential baseline monitoring parameters, 2) identification of geochemical processes which may alter those parameter values, and 3) prediction of potential chemical mass changes using thermochemical modeling calculations.

In Step 1, twenty Group I priority monitoring parameters are identified for a composite thermal water sampling from five KRGAs. Major constituents are Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, and SiO_2. Minor constituents are As^{3+}, B^{3+}, Ba^{2+}, F^{-}, Fe^{2+}, Li^{+}, Mn^{2+}, and NH_4^{+}. Essential solution parameters are temperature, pH, Eh, and TDS. The selections are based on a simple decision structure which tests each parameter against the requirements of thermochemical modeling and/or various water use standards.

For Step 2, five processes which can drive mass transfer reactions are described. Four are related to temperature, pressure, host mineral assemblage, and redox changes. The fifth, cation exchange, is also a function of the host mineral assemblage, but is considered as a separate process from mineral dissolution/precipitation reactions.

Inspection of reaction enthalpies and the Van't Hoff relation indicates that lowering of solution temperature could cause declines in aqueous Na^+, K^+, Ba^{2+}, Cl^-, F^-, and SiO_2. Depending on the host mineral environment, this could be accompanied by increases in Ca^{2+}, Mg^{2+}, and HCO_3^-.

Degassing caused by dropping fluid pressure can have various effects on the solution Eh and pH. Loss of CO_2 would cause a pH rise and possible precipitation of calcium carbonates or sulfates. Loss of H_2S gas would entail rises in both Eh and pH, while loss of O_2, perhaps more possible in injection waters, would have the opposite effect.

As an example of mineral exchange, calcite and gypsum dissolution from a new host rock could induce fluorite and barite or witherite precipitation from the geothermal fluid. These reactions imply net increases in aqueous Ca^{2+}, SO_4^{2-}, and HCO_3^- with declines in F^- and Ba^{2+}.

Redox changes can also cause the appearance of aqueous constituents initially present only as solids. Fe^{3+}, for example, stable as solid hematite under oxidized conditions in a shallow aquifer, could be mobilized as dissolved Fe^{2+} by an intruding geothermal water with lower redox potential. A number of trace elements, toxic in low concentrations, are also redox dependent.

Lastly, an example of cation exchange is described. Resultant exchanges of greater than 1,000 parts per million are demonstrated for clays of average exchange capacity exposed to saline solutions.

Linked by a large number of interdependent solution speciation reactions, the above mass transfer reaction processes are also interdependent. Prediction of potential mass transfers for monitoring purposes (Step 3) therefore requires simultaneous solution of all species mass action equations to obtain mineral saturation states for the fluid. This calculation, called the Class I speciation problem by Wolery (1979), requires several iterations for convergence and is best solved by computer methods. Several Class I programs are considered and an example result is given to model mineral solubility changes with declining temperature in a geothermal water. SOLMNEQ, a program by Kharaka and Barnes (1973) is recommended as being more applicable to Class I type geothermal problems.

Class II programs, capable of quantifying chemical mass transfers under more complex, Step 3 modeling constraints, are also evaluated. Results from MIX2 (Plummer, et al., 1975) compared well with laboratory results for mixtures of thermal and non-thermal waters. EQ3/6 (Wolery, 1979), however, computes speciation and mass transfer reactions for all five processes (temperature, pressure, and redox dependencies, open system mineral reactions, and cation exchange) and is recommended for geothermal modeling applications. Final choice of model constraints and programs required must rest with the geochemist most familiar with the site-specific problems.

SELECTION OF CHEMICAL PARAMETERS

Substantial gains have been made in recent years in documenting geothermal chemistries for the Western United States and the potential for salinity and trace element contaminations of usable water supplies by geothermal waste releases (Chen, et al., 1976; Geonomics, 1978; Summers, et al., 1980). Rather than reproduce that effort, existing data will be used to demonstrate a decision making process for monitoring parameter selection.

To begin, sample analyses from nineteen locations were taken from the literature as examples. The chemical data considered were taken primarily from the Raft River (Spencer and Callan, 1980; Cosner and Apps, date unknown) Roosevelt Hot Springs (Harding and Lawson, date unknown), and East Mesa (Geonomics, 1978) KGRA's. Several additional geothermal well samples from the Klamath Falls and Salton Sea KGRA's (Geonomics, 1978) were also included. An attempt was made to select the chemical data sets based on their being 1) representative of the KGRA in question, 2) relatively complete in terms of characteristic solution parameters (temperature, pH, TDS, and major ions), and 3) reasonably complete in terms of environmentally hazardous trace elements commonly associated with geothermal waters. The water quality data from the above five KGRA's are listed in Appendix C.

Starting with a series of recommended and maximum tolerance standards (Freeze and Cherry, 1979; Davis and DeWiest, 1966; EPA, 1976a; EPA, 1976b; Economic Research Service, 1962) for water use, a number of chemical parameter scores were developed for the sample analyses from the five KGRA's. In each case, the raw score is represented as a fraction, x/y, where x is the number of times the parameter exceeded a given water use standard and y is the number of times that parameter was measured and reported out of the nineteen samples.

In scoring the standards "violations," the following rules were used: 1) questionable data were excluded; 2) values below detection limit were included in the scoring when the detection limit was below the standard and excluded when the detection limit was greater than the standard; 3) "trace" data were excluded where the standard was less than or equal to 1.0 mg/l (milligrams per liter) and were counted where the standard was greater than 1.0 mg/l (this assumes that the geothermal constituent could have been quantified in the 1.0 mg/l concentration range); 4) averages were used for the livestock TDS standard range and the drinking water fluoride standard range; 5) with some small percentage error, parts per million (ppm) data units were assumed equivalent to mg/l data units.

The water use standards and the resulting cumulative scores for forty chemical parameters from the nineteen samples are given in Table 9.1. Additionally, each parameter on this table is assigned to one of three priority groups.

Group I is the essential monitoring parameter group, being necessary information to chemical calculation or being generally found in excessive amounts as a toxic or hazardous substance. These selections in particular are represented as a decision matrix in Table 9.2. For hazardous substances an arbitrary cutoff, called the 40/50 rule, was used. By this is meant that a substance to be included in Group I must exceed a given standard in at least 40 percent of the times measured and be measured in at least 50 percent of the samples taken.

Several trace elements were not included in Group I, primarily for lack of information. Nickel, for example, exceeds the drinking standard 33% of the times it was measured, but was only measured 6 times out of the nineteen samples considered. Several others were measured less frequently, but are toxic in low concentrations and were generally in excess of the standards where measured. The most significant among these are cadmium, chromium, lead, antimony, selenium, and mercury (Cd, Cr, Pb, Sb, Se, and Hg respectively). As can be seen in Appendix C, these elements comprise only a very small portion of the total dissolved solids. As such, they can have very little influence on the solution equilibria of a geothermal water and are nonessential parameters in that respect.

Group II priority assignments were therefore applied to those parameters which are not essential to chemical calculation, but which may be deleterious in a few site-specific instances or should be spot-checked in a newly developed area. Group III priority assignments represent those parameters which are unimportant to chemical calculations, do not have any use standards, and are generally below detection limits or are unaccounted for in the geothermal waters. With only a few exceptions the Group I and Group II parameters coincide with the problem constituents identified for a larger number of KGRAs by Summers, *et al*., (1980).

TABLE 9.1 ENVIRONMENTAL HAZARD SCORES AND PRIORITY GROUP ASSIGNMENTS FOR 40 CHEMICAL PARAMETERS FROM 19 GEOTHERMAL WATER SITES (APPENDIX C)

	Drinking Std. (D)	Irrigation Std. (I)	Livestock Std. (L)	Violation Scores			Priority Group Assignment	Redox Dependent*	Cation Exchange
				D	I	L			
Temp.							I		
Eh							I		
pH	5-9			2/19			I		
TDS	500	700	3-7K	19/19	19/19	19/19	I		
As	.05	.1	.2	8/10	7/10	5/10	I	X	
Al		1.0			2/11		II		
B	1.0	.75	5	11/15	12/15	9/15	I	X	
Ba	1.0			5/12			I		
Be		.1-.5			1/7		III		
Ca	200			4/19			I		X
Cd	.01	.01	.05	1/5	1/5	1/5	II		
Cr	.05	0.1	1.0	2/6	2/6	2/6	II	X	
Fe	.3			6/11			I	X	X
K							I		X
Li		.50		8/16			I		X
Mg	125			0/19			I		X
Mn	.05	2.0		6/10	2/10		I	X	
Na	200			17/19			I		X
Ni	1.0	0.5		2/6	2/6		II		
Pb	.05	5	0.1	6/8	2/8	6/8	II		
Sr							II		
Cu	1.0	0.2		1/5	1/5		II	X	
Zn	5.0	5.0		1/4	1/4		II		
Cl	250			17/19			I		
I							III	X	
F	1.4-2.4	1	2	10/17	15/17	9/17	I		
PO_4							III	X	
SO_4	250			2/19			I	X	
S							III	X	
NO_3	45		45	0/11		0/11	III	X	
HCO_3	500			3/19			I		
CO_3							III		
SiO_2							I		
NH_4	.02			12/12			I	X	
$Si(OH)_4$							III		
Sb	.01			4/4			II	X	
Se	.01	.02	.05	2/3	2/3	2/3	II	X	
Hg	.002		.01	2/5		2/5	II	X	
Ag	.05			1/5			III		
Mo	.01			0/4			III	X	

*redox dependencies are based on the element in question having more than one valence state obtainable in the presence of water.

TABLE 9.2 DECISION MATRIX FOR SELECTION OF GROUP I PRIORITY MONITORING PARAMETERS

Selection Criteria				
Essential to thermo-calculation as a solution parameter (A) or major constituent (B)		Violation of the 40/50 rule in Drinking (D), irrigation (I), or Livestock (L) standards** standards **		
A	B	D	I	L
Temp.				
Eh				
pH				
TDS*		TDS	TDS	TDS
	Ca^{2+}			
	Mg^{2+}*			
	Na^{2+}	Na^{+}		
	K^{+}			
	HCO_3^{-}			
	SO_4^{2-}			
	Cl^{-}	Cl^{-}		
	SiO_2			
		F^{-}	F^{-}	F^{-}
		$Fe^{2+,3+}$		
		Li^{+}		
		$Mn^{2+,4+}$		
		NH_4^{+}		
		Ba^{2+}		
		$As^{3+,5+}$	$As^{3+,5+}$	A
		B^{3+}	B^{3+}	$Bs^{3+,5+}$
				$^{3+}$

*TDS and Mg^{2+} are included here only because they are so commonly used as comparison data between natural water chemistries

**for definition of 40/50 rule see text (page 135)

In summary, twenty Group I monitoring parameters have been selected considering their importance as hazardous substances or as necessary thermochemical modeling data. It is not intended that these parameters be monitored at all KGRAs. Rather, the selection represents a decision-making process applied to a suite of geothermal water samples, which could be considered as coming from an imaginary KGRA.

GEOCHEMICAL REACTION TYPES

Background

The concentration of an aqueous component expresses only its total abundance in the solution. Nothing is implied, however, concerning the different forms (species) that component assumes in solution or the relative amount of each form available for reaction (chemical activity). Sodium (Na^+), for example, can exist in aqueous combination with various anions as shown in Table 9.3, each species having its own activity.

TABLE 9.3 AQUEOUS SPECIES OF SODIUM AS GIVEN BY TRUSEDALE AND JONES (1974)

Species and Charge	Associated Ion	Species Type
Na^+	none	free ion
$NaCl^\circ$	CL^-	neutral ion pair
$NaCO_3^-$	CO_3^{2-}	charged complex
$NaHCO_3^\circ$	HCO_3^-	neutral complex
$NaSO_4^-$	SO_4^{2-}	charged complex
$Na_2CO_3^\circ$	CO_3^{2-}	neutral complex
$Na_2SO_4^\circ$	SO_4^{2-}	neutral complex

When one considers that other cations can also form ion pairs and complexes with the anions shown in Table 9.3, the number of possible speciation reactions in a solution becomes fairly large. Treating the free electron activity as another solution component, further speciation due to redox reactions must also be considered.

The Law of Mass Action therefore requires that all speciation reactions in solution be at equilibrium interdependently. That is, speciation calculations for multi-component natural solutions require the simultaneous mathematical solution of n equations (reactions) in n unknowns (species).

Speciation calculations for geothermal waters can be used in several ways. Certain species involved in mineral dissolution/precipitation reactions can be used to calculate mineral saturation indices. The latter can be used to indicate the potential for gain or loss of aqueous constituents through mineral reactions. This can be particularly important in situations where a geothermal water is caused to re-equilibrate to a new environment as a result of 1) loss of dissolved gases due to pressure reduction, 2) loss of temperature from thermal extraction or leakage into a cooler ground-mass, and/or 3) contact with a new mineral suite, which may also include contact with oxidized materials. These effects can be predicted in a general sense by calculating mineral saturations in geothermal waters under the various end-member stresses. Lastly, gain or loss of certain aqueous species may occur as a result of cation exchange reactions with nonthermal aquifer materials.

The reaction types proposed for this study have been reduced to five basic categories; 1) temperature dependent solution/precipitation reactions, 2) pressure dependent solution/precipitation reactions, 3) mineral-mineral solution/precipitation reactions, 4) redox dependent solution/precipitation reactions, and 5) cation exchange reactions. These reaction types will be considered separately in the following sections.

Temperature dependent solution/precipitation reactions.

The saturation index (SI) of a mineral is defined as

$$SI = \log (IAP/K_{sp}) \qquad (1)$$

where IAP is the activity product and K_{sp} is the solubility product for a mineral dissolution reaction. For example, the dissolution/precipitation of fluorite (Ball, et al., 1980)

$$CaF_2 \text{ (fluor)} \rightleftarrows Ca^{2+} + 2F^- \qquad (2)$$

has an ion activity product defined as

$$IAP = \frac{(aCa^{2+})(aF^-)^2}{(aCaF_2)} \qquad (3)$$

where (aX) denotes the activity of ion X in a solution as thermodynamically calculated from the solution parameters. By definition, the activity of a pure crystalline solid (in this case, fluorite) equals unity. This reduces expression (3) to a simple product of the aqueous reaction products, calcium and fluoride. The solubility product, K_{sp}, is the theoretical value of IAP for a solution in equilibrium with the mineral, corrected to the solution temperature. If the activity product of ions in a solution is greater than the solubility product, the SI value is positive and the solution is said to be supersaturated with respect to the mineral. Conversely, if IAP<K_{sp}, the SI value is negative and the solution is undersaturated. If the solution is supersaturated mineral precipitation is possible. If undersaturated, dissolution of the mineral is possible if it is present in the surrounding solids.

In calculating saturation indices for concentrated waters, several points must be observed. They are:

1) Aqueous complexing of ions must be calculated in advance. The fluorite reaction, for example, depends only on the calcium and fluoride ionic species indicated, not on the total dissolved amounts of calcium and fluoride in the solution.
2) By Debye-Huckel theory (Truesdell and Jones, 1974), activities of species can be considerably less than their molal concentrations and must be calculated, especially for solutions of high ionic strength.
3) K_{sp} must be corrected to the sample temperature.
4) The resulting saturation index only indicates the thermodynamic favorability for a given reaction to proceed. Because of kinetic effects, mineral dissolution (or precipitation) in some cases may not proceed rapidly enough for the effects to be immediately detectable.

Assuming that a temperature decrease will accompany geothermal energy production or leakage to a cooler aquifer, the temperature effect on mineral solubility must now be considered. The fundamental relationship is given by the Van't Hoff relation:

$$\log K_{sp} = \log K_r - \frac{\Delta Hr^{\circ}}{2.3R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \qquad (4)$$

where:

K_{sp} is the solubility product corrected for temperature (K_{sp} can be replaced by K_{eq} in the same relationship to correct equilibrium constants for aqueous speciation reactions).
T is the solution temperature in degrees Kelvin.
K_r is the solubility product (or equilibrium constant) for the reaction at the reference temperature.
T_r is the reference temperature (298.15°K).
ΔHr° is the enthalphy change for the reaction (not strictly a constant over large temperature ranges; may require correction in some cases).
R is the universal gas constant.

From this equation it can be predicted that for negative reaction enthalpy (exothermic reaction) a drop in solution temperature would cause an increase in the mineral solubility product. Conversely, for endothermic mineral dissolutions, dropping solution temperature will cause the solubility product to decrease.

The latter is the case for the fluorite solubility example. If a geothermal water is initially undersaturated at high temperature with respect to fluorite, a large temperature drop could decrease the solubility product to a point where precipitation would become favorable. Fluorite precipitation would then reduce the dissolved calcium and fluoride concentrations in the fluid.

Solubility changes with decreasing fluid temperature are indicated for a selection of chloride, fluoride, sulfate, carbonate, and silica minerals in Table 9.4. Assuming the presence of several common minerals in an intruded, low-temperature aquifer, a cooling geothermal fluid could undergo a general loss of chlorides, fluorides, and silica with an increase in aqueous carbonates and perhaps an exchange of some sulfates. With regard to cations, general declines in aqueous sodium, potassium, and barium and an increase in aqueous calcium and magnesium might be expected for a cooling geothermal water. Any or all of these chemical mass transfers would result in readjustment of the entire solution speciation balance.

Pressure dependent solution/precipitation reactions.

At a given temperature, the pressure effect on solubility products (K_{sp}) and aqueous speciation equilibrium constants (K_{eq}) is described by the expression:

$$\log K_{sp} = \log K_r - \frac{\Delta V^\circ r}{2.3RT} (P - P_r) \qquad (5)$$

here:

K_{sp}	is the solubility product or equilibrium constant corrected to the pressure of interest.
T	is the temperature of the solution in degrees Kelvin.
K_r	is the solubility product or equilibrium constant at the reference pressure.
P_r	is the reference pressure (1 atmosphere).
P	is the pressure on the solution of interest.
ΔV°	is the net molal volume change for the reaction.
R	is the universal gas constant.

The net molal volume change is usually negative for mineral dissolution and species association reactions. Equation (5) then implies a decrease in ion complexing and mineral solubility with

TABLE 9.4 SOLUBILITY CHANGES FOR CHLORIDES, FLUORIDES, SULFATES, BONATES, AND SILICA RESULTING FROM DECREASING FLUID TEMPERATURE

Mineral	Composition	H dissolution (Kcal/mole)	Solubility increase with Temp. drop	Solubility decrease with Temp. drop	Source	Comment
halite	NaCl	+ .918		X	(1)	
sylvite	KCl	+4.112		X	(2)	
	$CaCl_2$			X	(3)	
	$MgCl_2$			X	(3)	
fluorite	CaF_2	+4.710			(1)	
	BaF_2	+1.0			(4)	
thenardite	Na_2SO_4	-0.572	X	X*	(1),(3)	Solubility max at 200°C
mirabilite	Na_2SO_4 $10H_2O$	+18.987		X	(1)	
	K_2SO_4		X	X*	(3)	Solubility max at 250°C
gypsum	$CaSO_4 \cdot 2H_2O$	+0.261	X			
anhydrite	$CaSO_4$	-3.769	X		(1)	
barite	$BaSO_4$	+6.28		X	(1)	
	$LiSO_4$		X		(3)	data below 200°C only
calcite	$CaCO_3$	2.585	X		(1),(3)	
thermonatrite	$Na_2CO_3 \cdot H_2O$	-2.802	X		(1)	
witherite	$BaCO_3$	+0.36		X*		probably only in low temp range
siderite	$FeCO_3$	-5.328	X		(1)	
dolomite	$CaMg(CO_3)_2$	-8.290	X		(1)	
chalcedony	SiO_2	+4.615		X	(1)	
quartz	SiO_2	+6.220		X	(1)	
amorphous SiO_2	SiO_2	+4.44		X	(1)	

*lower temperature range tendency.
(1) Ball, Jenne, and Nordstrom, 1978.
(2) Garrels and Christ, 1965.
(3) Ellis and Mahon, 1977.
(4) Ball, Nordstrom, and Jenne, 1980.

a decline in pressure. Because of the very small ΔV° values for these reaction types, the pressure effect is generally insignificant when compared to the temperature effect and can be ignored (Krauskoff, 1967). It is important, however, when considering gas solubilities.

Chemically reactive dissolved gases in geothermal water might typically include CO_2, H_2S, O_2, CH_4, and NH_3 (Geonomics 1978; Cosner and Apps, date unknown; White, 1978). The activities of these dissolved gases (as individual species) are dependent on both the Eh and pH of the solution. Redox reactions will be considered in a later section. Of importance here is that dissolution of these gases into the aqueous phase is accompanied by large negative molal volume changes. Equation (5) then describes the much greater solubility of gases under high pressure and how release of that pressure would promote degassing from the fluid.

Degassing of CO_2, for example, would effect the solution pH as described by the following reactions:

$$H_2CO_3^\circ \rightarrow H_2O + CO_2(gas) \qquad (6)$$

$$HCO_3^- + H^+ \rightarrow H_2CO_3^\circ \qquad (7)$$

By the law of Mass Action, loss of CO_2 gas from the right side of reaction (6) would cause a corresponding shift in reaction (7) to replace some of the carbonic acid consumed. The net result is a decrease in free hydrogen ion activity (as well as bicarbonate ion), corresponding to a pH rise.

Loss of hydrogen ion activity can affect the whole solution speciation balance upon which mineral saturation states depend. Reactions (8), (9), (10), and (11) depict two examples of pH dependent speciation shifts which would bring two calcium minerals closer to saturation or even cause their precipitation.

$$HCO_3^- \rightarrow H^+ + CO_3^{2-} \qquad (8)$$

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3(\text{calcite}) \qquad (9)$$

$$HSO_4^- \rightarrow H^+ + SO_4^{2-} \qquad (10)$$

$$SO_4^{2-} + Ca^{2+} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O\ (\text{gyspum}) \qquad (11)$$

Removal of hydrogen ion from the right hand sides of reactions (8) and (10) results in reaction shifts to the right to maintain equilibria. This creates more free carbonate and sulfate. The increased carbonate and sulfate activities raise the ion activity products of calcite and gypsum, bringing them closer to saturation and the possibility of precipitation. Notice in this case that mineral saturation states have been altered by a change in activity products from speciation shifts, rather than by a change in solubility products due to a shift in solution temperature.

Degassing of H_2S and O_2 are represented by reactions (12) and (13). Again, loss of gas components on the right hand

$$SO_4^{2-} + 10H^+ + 8e^- \rightarrow 4H_2O + H_2S \text{ (gas)} \qquad (12)$$

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2 \text{ (gas)} \qquad (13)$$

sides of the reactions cause corresponding chemical shifts in that direction to maintain the respective equilibria. Noting the free hydrogen molal changes, reaction (12) implies a rise in solution pH, and (13) implies a pH drop. Also, the free electron activity changes represent changes in solution redox potential. Loss of H_2S gas would tend to make the solution more oxidizing, while loss of oxygen would tend to make it more reducing.

It is not known which of these reactions would predominate, but it might be hypothesized that reaction (12) would be more important in situations involving leakage during production. Reaction (13) may apply more strongly during waste-water injection, where well failure could cause loss of injection pressure.

Mineral-mineral solution/precipitation reactions.

In many cases, neither temperature nor pressure changes may be required for solution chemistry changes to occur. A geothermal water equilibrated to its reservoir rock materials at depth is unlikely to also be equilibrated to the mineral assemblage in a newly intruded aquifer.

Consider as an example a geothermal water which is undersaturated with respect to calcite and gypsum and near the saturation point with respect to barite, witherite, and fluorite. If such water were to be released into an aquifer containing calcite and gypsum, these minerals would begin to dissolve (reverse reactions (9) and (11)), causing a net increase in aqueous calcium, carbonate, and sulfate. Steady increases in calcium could raise the activity product of fluorite to the point of supersaturation, causing fluorite precipitation:

$$Ca^{2+} + 2F^- \rightarrow CaF_2 \text{ (fluorite)} \qquad (14)$$

Correspondingly, increasing aqueous carbonate and sulfate could cause supersaturation and precipitation of witherite and/or barite, respectively:

$$Ba^{2+} + CO_3^{2-} \rightarrow BaCO_3 \text{ (witherite)} \qquad (15)$$

$$Ba^{2+} + SO_4^{2-} \rightarrow BaSO_4 \text{ (barite)} \qquad (16)$$

The latter two reactions are competitive for barium, and precedence would depend on which mineral reached the saturation point first. Even this assumes that the solid mineral phase in question would be stable under the Eh-pH constraints of the solution, since the carbonate speciation is pH dependent and the sulfur speciation is both Eh and pH dependent. The net result of these example reactions would be increases in aqueous calcium, sulfate and carbonate, accompanied by decreases in barium and fluoride.

Redox Reactions

Measurement of Eh and subsequent considerations of redox reactions are important in the design of geothermal monitoring systems primarily because of potential for rapid changes in water chemistry. If these chemical changes are not understood and/or anticipated, monitoring data may be difficult to interpret.

Redox reactions involve a valence change (loss or gain of electrons) for one or more elements in rocks or water. When an electron is exchanged between two elements, the electron acceptor becomes reduced while the donor becomes oxidized. The redox potential (Eh) of a solution is essentially a function of the ratio of oxidized to reduced species. More formally:

$$Eh = E^\circ + \frac{RT}{nF} \log \frac{\text{oxidized species}}{\text{reduced species}} \qquad (17)$$

Where:

E° is a standard half-cell potential
R is the gas constant
F is the Faraday constant
T is absolute temperature in °K
n is the number of moles involved in reaction

Eh can be measured for solutions by measuring the potential across an electrode pair in contact with the solution. This pair usually consists of a platinum electrode and a calomel reference electrode of known electromotive potential. If the concentrations of both ions in a single redox couple are known, say Fe^{2+}/Fe^{3+}, then a slight modification of equation (17) can also be used to determine the solution Eh. In this case, E° would be the standard half-reaction potential for the oxidation of Fe^{2+} to Fe^{3+}.

Two other methods may be utilized to determine, in a relative sense, the oxidation-reduction potential of various solutions. The first is the presence or absence of substances such as H_2S which, even in limited concentrations, is relatively easy to detect in the field due to the distinct smell. If H_2S is detected the general Eh may be determined from Figure 9.1 if the pH is known.

The measurement of dissolved oxygen also provides a method of determining the oxidation potential of a given fluid. This determination is generally accomplished using a special electrode and proves to be quite accurate down to levels of <1 ppm dissolved oxygen. If dissolved oxygen is present, Eh measurements are questionable because reduced ions should be oxidized. If these ions are oxidized then (according to Equation 17) Eh would be meaningless. The presence of reduced species and dissolved oxygen generally implies a nonequilibrium condition caused by slow reaction rates. These nonequilibrium conditions are transient and will normally change rather rapidly.

Therefore, the Eh of a system may be estimated by the presence or absence of substances such as H_2S, measured with an Eh electrode under generally reducing to moderately oxidizing conditions, or determined with a dissolved oxygen meter under more oxidizing conditions.

The general redox conditions that could exist if a geothermal fluid were to leak into a cold aquifer are that of a generally reducing geothermal fluid and an oxidized groundwater. The geothermal fluids are generally thought to be reducing (oxygen depleted) as indicated by the smell of H_2S, or lack of dissolved oxygen. Conversely, groundwaters generally have measurable dissolved oxygen and contain ions in an oxidized state. Therefore, if reducing geothermal fluids were to enter an oxidized aquifer-groundwater system, numerous rapid reactions could take place.

Many elements including those listed on Tables 9.1 and 9.5, exhibit various valances and most have different solubilities in water at the different valances. Iron will be used to illustrate how the system will react if geothermal fluid were to leak into an aquifer system. The Eh values shown on Figure 9.1 illustrate expected values for normal aquifer water of +0.2 volts (+200 mv) at point (1), and an expected Eh of -0.25 volts (-250 mv) for geothermal fluids at point (2). The latter is consistent with the presence of H_2S in many geothermal fluids at a pH of 6 to 7. The scenario is that thermal waters with a low Eh (-250 mv) would flow in to an aquifer equilibrated to an Eh of +200 mv and immediately the Eh of the aquifer system would drop to approximately -250 mv. Then, using Figure 9.2, it is easy to predict what will happen to the iron concentrations in the aquifer in question. The Eh in the aquifer will drop from point (1) to (2) (Figure 9.2) and in doing so will change from the stability field of hematite to the Fe^{2+} field. The contour lines in the Fe^{2+} field represent total iron activities. Point (2) is on the -3 line and therefore represents the potential for this water to

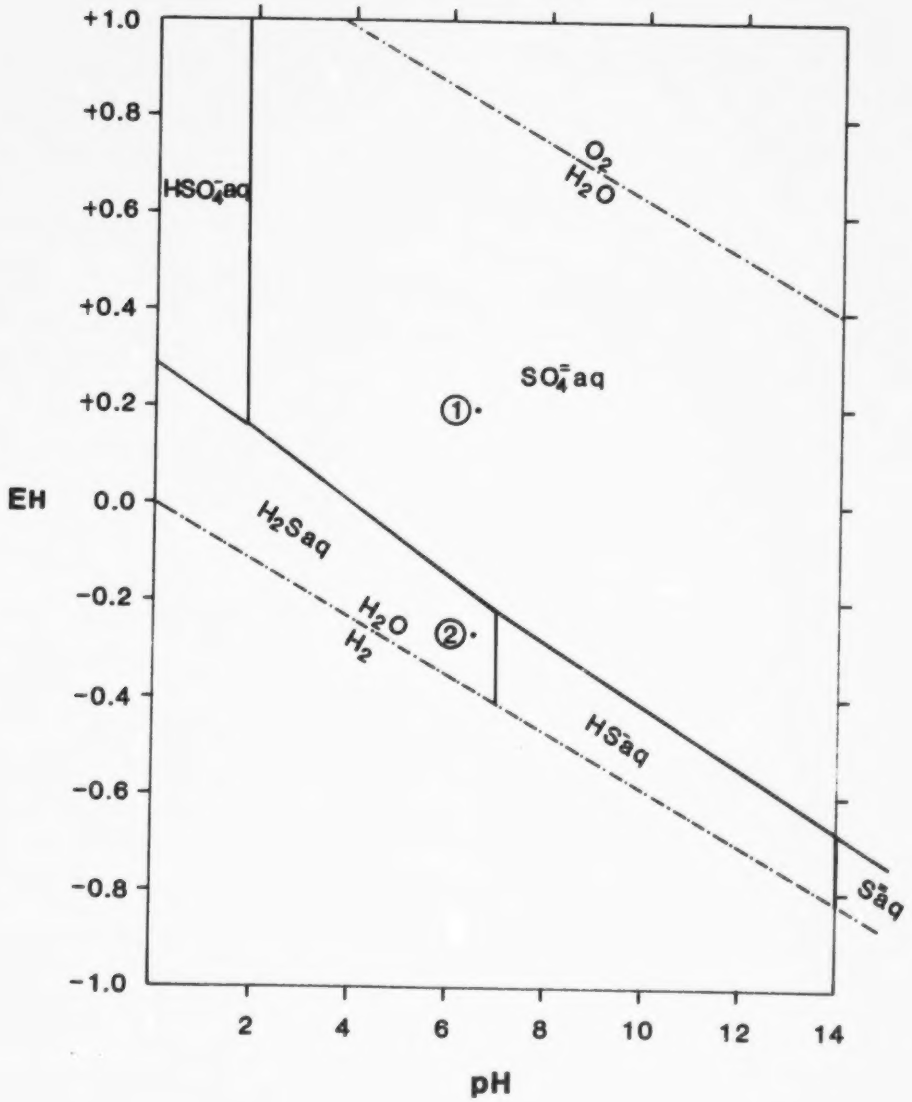

Figure 9.1 Equilibrium distribution of sulfur species in water at 25°C and 1 atmosphere total pressure (From Garrels and Christ, 1965)

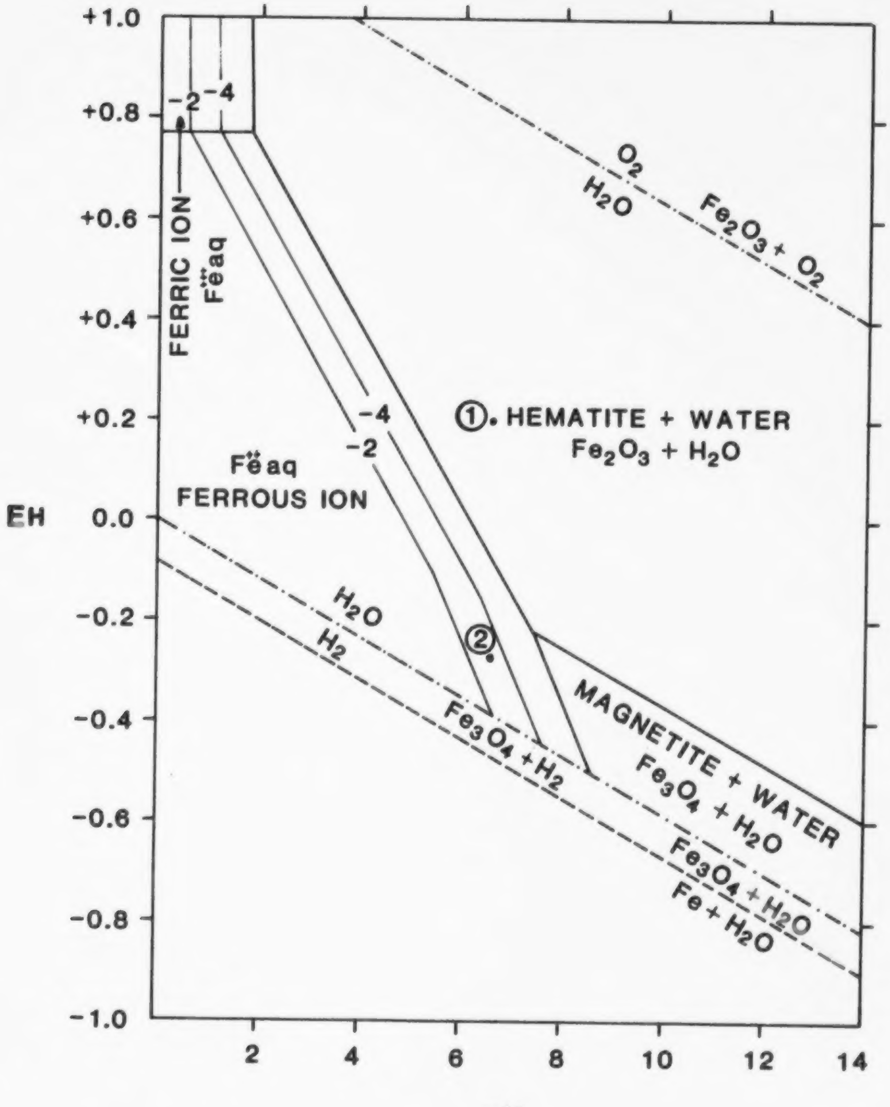

Figure 9.2 Composite diagram showing stability fields of Hematite and Magnetite in water. Fields of ions are designated where total activity of dissolved species are $>10^{-6}$. Fields of ions are labeled with dominant species. Contour of log [dissolved species]= -4 is included to show slope of activity change. Plot at 25°C and 1 atmosphere total pressure (From Garrels and Christ, 1969)

TABLE 9.5 PARTIAL LIST OF ELEMENTS WITH DIFFERENT VALENCES EXPECTED TO BE IMPORTANT IN GEOTHERMAL SYSTEMS

Arsenic	-3, 0, +3, $\underline{+5}$
Cobalt	+1, $\underline{+2}$, $\underline{+3}$, +4
Chromium	+2, $\underline{+3}$, $\underline{+6}$
Copper	0, $\underline{+1}$, $\underline{+2}$, +3
Iron	0, $\underline{+2}$, $\underline{+3}$, $\underline{+6}$
Mercury	0, +1, $\underline{+2}$
Manganese	$\underline{+2}$, +3, $\underline{+4}$, +5, +6, +7
Molybdenum	+2, +3, $\underline{+4}$, +5, $\underline{+6}$
Nitrogen	$\underline{-3}$, $\underline{0}$, +1, +2, +3, +4, +5
Nickel	+1, $\underline{+2}$, +3
Sulfur	$\underline{-2}$, $\underline{0}$, +3, +4, +5, $\underline{+6}$
Selenium	$\underline{-2}$, 0, +4, +6
Uranium	+3, $\underline{+4}$, +5, $\underline{+6}$
Vanadium	+2, +3, +4, $\underline{+5}$
Tungsten	+2, +3, +4, +5, $\underline{+6}$

$\underline{+5}$ indicates the most common valence(s).

dissolve up to 55 mg/l iron. If any iron is present in an oxidized form in the aquifer it will rapidly be dissolved, up to a maximum of 55 mg/l. The contour lines represent order of magnitude changes in that -4 is 5.5 mg/l iron and -6 is 0.055 mg/l Fe^{2+}.

The importance of this information in monitoring groundwater quality is that ions that are not present in either the geothermal fluid or the groundwater may appear in large quantities and present a contamination problem. This is possible because aquifer water at point (1) (Figure 9.2) would have less than 0.05 mg/l Fe^{2+} and the geothermal fluid at point (2) would have the potential to dissolve iron but none may be present in the geothermal system, so iron concentration would also be negligable. If this were the case, then neither water would contain any iron during initial background sampling and therefore, iron may be eliminated as a problem. This would be an obvious error and could lead to problems. The problem could even be more acute with many trace metals, unlike iron, that are toxic in the parts per billion range.

A two-fold attack on this problem should be undertaken. The first would be to run the appropriate geochemical model to anticipate what ions may be mobilized. Second, if leaks are detected, water samples should be analyzed for a broad spectrum of ions and not just those observed in either the geothermal fluids or the groundwaters.

Cation Exchange Reactions

Cation exchange reactions may profoundly change the chemistry of water passing through minerals that have measureable cation exchange capacity (CEC). Clay minerals, zeolites and several other minerals will readily exchange ions with water and therefore change the expected water chemistry. This chemical change could drastically affect the implementation of a water quality monitoring plan by modifying the expected water chemistry. The ion ratios may be totally changed such that geothermal fluids leaking into certain aquifers may change to the point that they are unrecognizable as geothermal fluids.

Clay minerals, zeolites, and certain other minerals have the property of sorbing certain cations and anions and retaining them in an exchangeable state. These ions are generally exchangeable with other ions from aqueous solutions. The exchange reaction is stoichiometric and thereby differs from simple sorption; however, it is sometimes difficult to distinguish since nearly every ion exchange process is accompanied by sorption or desorption.

The exchangeable ions are held around the outside of the silica-alumina clay-mineral structural unit, and the exchange reaction generally does not affect the crystal structure. A well-known example of the ion-exchange reaction is the softening of water by passing it over zeolites. This simple single-pass exchange system is effective in totally changing the cation composition of the water.

Cation exchange capacity is normally measured and reported in terms of milliequivalents per 100 gm. One equivalent of Na^+ expressed as Na would have a weight of 23, and 1 meq/100g would be equal to 0.023 percent Na.

There is currently more information available regarding cation exchange than anion exchange. The most commonly exchanged cations, in approximate order of relative abundance in minerals are Ca^{2+}, Mg^{2+}, H^+, K^+, NH_4^+, and Na^+ (Table 9.6). The most common anions are SO_4^{2-}, Cl^-, PO_4^{3-}, and NO_3^-, though their relative abundance is unknown and little research is available on the subject.

The causes of cation exchange of the above ions with various minerals may be divided into 3 basic groups (Grim, 1968).

1. Broken bonds around the edges of the silica-alumina units give rise to unsatisfied charges, which would be balanced by adsorbed cations. The number of broken bonds and hence the exchange capacity due to this would increase as the particle size decreased. Lattice distortions would also tend to increase broken bonds, and the exchange capacity would be expected to increase as the degree of crystallinity decreased.
2. Substitutions within the lattice structure of trivalent aluminum for quadrivalent silicon in the tetrahedral sheet and ions of lower valence, particularly magnesium, for trivalent aluminum results in unbalanced changes in the structural units of some minerals.
3. The hydrogen of exposed hydroxyls may be replaced by a cation which might be exchangeable.

It seems apparent that if exchangeable cations/anions exist in thermal waters and if exchangeable minerals exist in various aquifers, these may mix when a leak occurs and the above described reactions will take place.

Carefully documented examples of geothermal fluids moving through aquifers with exchangeable minerals are unobtainable. Therefore, data from Russell (1970) was used to illustrate what might happen under certain circumstances similar to those described above.

The experiments involved mixing a water similar to sea water which is not unlike some geothermal fluids, with a clay having a CEC of 76 meq/100gm. A CEC of 76 is an average to high value (Table 9.6).

The following summarized results (Table 9.7) exhibit the types of changes that may be expected. The original sea water concentrations are from Turekion (1968) and the exchangeable cations on the clays are after Russell (1970).

TABLE 9.7 CATION EXCHANGE CALCULATIONS DEMONSTRATING CHANGES IN WATER CHEMISTRY DUE TO CATION EXCHANGE

Clays Cation	Original Clay (meq/100g)	Dry Clay (meq/100g)
Ca^{2+}	48	17
Ng^{2+}	10	38
K^+	12	4

Water Species	Molality	eqiv/l	original concentrations (mg/l or ppm)	equiv/l with 3:1 mixture H_2O:clay by weight	concentrations after exchange (ppm)
Ca^{2+}	0.0104	0.021	416	0.114	2280
Mg^{2+}	0.054	0.108	1312	0.024	292
K^+	0.010	0.010	391	0.034	1330

The calculated changes in both the clays and water are substantial within the given framework of a 3:1, H_2O: clay based on weight. This example is based on an aquifer having approximately ten percent exchangeable clays and approximately 30 percent porosity with a void space being replaced with geothermal fluid only once, and no mixing.

The water changes are of special interest and show concentration changes in Ca^{2+} from 416 to 2280 ppm, Mg^{2+} from 1312 to 292 ppm, and K^+ from 391 to 1330 ppm. The changes are dramatic enough that the two waters might not be recognized as being similar unless cation exchange was considered and incorporated in the monitoring design.

TABLE 9.6 CATION EXCHANGE CAPACITY FOR SELECTED MINERALS

Mineral	CEC (meq/100gm)
Clays[1]	
Kaolinite	1-10
Montmorillonite	80-140
Illite	10-40
Chlorite	5-30
Vermiculite	100-180
Zeolites[2]	
Natrolite	530
Thomsonite	620
Stilbite	320
Heulondite	330
Analcime	450
Mordenite	230
Chabasite	400

[1] Berner, 1971.

[2] Barrer, 1978.

GEOCHEMICAL MODELING COMPUTER PROGRAMS

Background

Wolery (1979) assigns solution chemistry problems to two classes; Class I problems being related to the solution speciation equilibria and resulting mineral saturation states, and Class II problems pertaining to changes in the dissolved component masses resulting from mineral solution/precipitation reaction models.

In advanced geochemical programming practice, these two problems are stepwise interdependent. That is, results from a Class I problem are required before the first step in a Class II mineral reaction progress can be calculated. Then the Class I speciation/saturation problem must be recalculated to adjust the solution to the net reactant mass changes calculated in the prior Class II step. This new Class I solution state is then used to direct the next Class II mineral reaction progress, and so on. Models of this type are meant to imitate natural systems where disequilibria between solid and aqueous phases occur.

Class I Programs

Alone, Class I calculations and results are useful in that 1) they can be used to predict the dominating species in which a given chemical component is transported, 2) they can be used to predict the ability of a water to dissolve or precipitate certain minerals based on their relative saturation indices, and 3) they can be computed without quantitative knowledge of the aquifer mineralogy, although some semiquantitative mineralogical information is generally useful to interpretations.

The complexity of thermodynamic calculations for large numbers of interdependent speciation reactions has been indicated earlier. The following list details the types of calculations and computational processes, in order, typically used to solve the Class I problem. The calculation sequences, generalized from SOLMNEQ (Kharaka and Barnes, 1973) and the WATEQ series (Truesdell and Jones, 1974; Plummer, *et al*., 1976; Ball, *et al*., 1978) geochemical programs, demonstrate the real complexity of the Class I problem and the need for computerized techniques.

1. Correction of all standard reaction equilibrium constants and solubility products to the solution temperature of interest using:
    a) the Van't Hoff relation;
    b) empirical expressions derived from analytic data;
    c) an extended, integrated form of the Van't Hoff

expression requiring precalculation of reaction heat capacity by the Maier-Kelley power functions (Kharaka and Barnes, 1973); or

d) an expression equating the equilibrium constant to a function of standard reaction enthalpy, entropy, temperature, and a series of temperature-independent solvent constants (Kharaka and Barnes, 1973).

2. Conversion of input chemical concentration units to molal units using solution density and other thermochemical constants.
3. Calculation of free electron activity from measured Eh, dissolved oxygen, or various redox couples.
4. Calculation of the temperature effect on solvent constants used in the Debye-Huckel equation for determining individual ion activity coefficients.
5. Calculation of the activity of water as a function of all dissolved species molalities (initially, all analyzed input totals are assumed to be in the free ion state; e.g., all calcium is assumed to be present as Ca^{2+} ion, other calcium species having molalities equal to zero on the first iteration).
6. Calculation of solution ionic strength as a function of all charged ion molalities (again, the first iteration assumes all analyzed totals to be present as free ions).
7. Calculation of all ionic species activity coefficients using various forms of the Debye-Huckel equation (requires temperature corrected solvent constants, ionic strength, and the pertinent species charge, size, and 'b' parameters).
8. Using the "continued fraction" method of successive approximations (Nordstrom, et al., 1979), several tens to hundreds of individual speciation reactions are then solved simultaneously. This is accomplished by substituting all species formation (mass action) expressions containing a given ion into the mass conservation equation for that ion and solving for the free ion component. All free cations and anions are solved in this manner and then back-substituted into the species formation expressions to find the species concentrations. This calculation sequence must be repeated until the input and computed anion totals converge to within some specified error limit.
9. Each time the above iteration is performed, the activity of water, ionic strength, and species activity coefficients (items 5, 6, and 7 above) must be recalculated as part of the aqueous system constraints.

10. After the solution speciation problem has converged, the appropriate species can then be used to calculate ion activity products for a number of mineral dissolution reactions. Comparison of the activity products to the temperature-corrected solubility products then yields the mineral saturation indices.

The above sequence is generalized and ignores a number of additional complexities related to corrections for analytical methods, epm (equivalents per million) balance calculations, convergence error, and numerical error propagation due to uncertainties in thermochemical constant values. These problems are also addressed in geochemical programming practice, and efforts continue to 1) improve computational efficiency and accuracy, 2) refine thermochemical constant values, and 3) upgrade reaction mechanism lists to include those which appear to have the most bearing on the aqueous systems being evaluated (Ball, *et al*., 1980; Wolery, 1979; Nordstrom, *et al*., 1979).

Aside from the theoretical and computational problems, another issue is the quality of the water analyses used as input to these programs. A simple check would be to perform an epm balance on the water analyses. Chemical constituents not included in the laboratory analyses are assumed to have zero concentrations by all chemical programs, unless entered as educated guesses. If the missing constituent is a major contributor in the natural aqueous system, the calculated results will likely be correspondingly inaccurate. A trace element component, on the other hand, will generally have much less influence on the solution balance, and need not be included unless it is desirable to monitor the reactive state for that particular component. Such considerations are at least part of the rationale used in the chemical parameter selection methodology described earlier.

Solving the Class I speciation problem is therefore a nontrivial matter. Hand calculation of such a problem would be prohibitively time consuming. Once obtained, individual species concentrations and mineral saturation results must be interpreted with an understanding of the complicating factors involved. It is recommended that saturation indices, because of their logarithmic scale, be only interpreted in terms of relative orders of magnitude of supersaturation or undersaturation and/or relative change resulting from modeled system stresses (e.g., change of temperature).

As a test example, an aqueous analysis from the Phillips geothermal Well 54-3 at Roosevelt Hot Springs KGRA (Harding and Lawson, date unknown, Appendix C) was run on WATEQF at 100°C and also at 25°C. These runs converged in 10 iterations, calculating 48 species concentrations and 40 mineral saturation indices from 15 input chemical components. For reader interest, partial speciation results for these computer runs are given in Appendix D.

Saturation indices for selected common minerals from these computations are given in Table 9.8. These results are in excellent agreement with the qualitative predictions of solubility change with decreasing temperature summarized in Table 9.4 (increasing saturation index corresponds to decreasing solubility and vice versa). The Table 9.8 results, however, obviously add an important quantitative dimension to these predictions. Fluorite, for example, is undersaturated in this solution by over 50 orders of magnitude at both temperatures and is unlikely to precipitate as a result of temperature decline, in spite of the potential errors involved in calculating the index values. Barite, on the other hand, is slightly undersaturated at 100°C and slightly supersaturated at 25°C, implying the potential for barite precipitation with dropping solution temperature. This would take precedence over barium loss through witherite precipitation, unless the geothermal water increased significantly in aqueous carbonate concentration. The solution is undersaturated (at 25°C) with respect to both carbonates and sulfates (aside from barite), and could dissolve either, influencing the ultimate fate of barium. The latter question becomes a Class II type thermodynamic problem, which will be described in the next section.

The above examples demonstrate both the complexity and the usefulness of the Class I type geochemical programs. At a given geothermal development, such methods, combined with adequate aquifer mineralogy and water quality information, could be used to point out the most diagnostic chemical monitoring parameters.

Of the Class I geochemical programs reviewed, SOLMNEQ (Kharaka and Barnes, 1973) is recommended over WATEQF (Plummer, et al., 1976) for aqueous geothermal problems. SOLMNEQ considers all of the Priority Group I chemical parameters (described earlier) and a number of the Group II trace elements. WATEQ2 (Ball, et al., 1978) handles even more trace element species and minerals than SOLMNEQ, but, like WATEQF, thermodynamic treatment of reaction constants in this program is only generally valid for temperatures up to 100°C. Using interpolating tables of reaction constants determined by a number of sophisticated theoretical and experimental techniques, SOLMNEQ thermodynamic calculations are generally valid up to 350°C. In addition, SOLMNEQ also can be used to calculate the silica and Na-K-Ca geothermometers, ion exchange equilibria, and solution pressure dependencies.

For temperatures below 100°C, WATEQF can be used to determine measures of gross chemical tendency, and in terms of computer time and space, is probably more adaptable to small computers than the others. The chief advantage of WATEQ2 is that it handles speciation and mineral reactions for virtually all of the constituents shown on Table 9.1 (except beryllium, antimony, and selenium) and provides an up-to-date (Ball, Nordstrom, and Jenne, 1980) compilation of a large amount of useful thermodynamic information. Specifications and capabilities for these and other geochemical computer programs are summarized in Appendix E.

TABLE 9.8 MINERAL SATURATION INDEX RESULTS FOR PHILLIPS GEOTHERMAL WELL 54-3 AT ROOSEVELT HOT SPRINGS KGRA AS CALCULATED BY WATEQF AT 100°C AND 25°C

Mineral	Composition	Saturation Index at 100°C	Saturation Index at 25°C
halite	$NaCl$	-4.06	-3.89
fluorite	CaF_2	-55.76	-53.10
thenardite	Na_2SO_4	-5.96	-5.93
mirabilite	$Na_2SO_4 \cdot 10H_2O$	-7.93	-5.01
anhydrite	$CaSO_4$	-2.79	-3.15
gypsum	$CaSO_4 \cdot 2H_2O$	-2.78	-3.19
barite	$BaSO_4$	-0.79	+0.30
calcite	$CaCO_3$	-0.96	-1.98
thermonatrite	$Na_2CO_3 \cdot H_2O$	-8.38	-8.90
witherite	$BaCO_3$	-3.75	-3.75
siderite	$FeCO_3$	+0.51	-0.34
dolomite	$CaMg(CO_3)_2$	-2.64	-5.29
chalcedony	SiO_2	+0.76	+1.44
quartz	SiO_2	+1.01	+1.92
amorphous SiO_2	SiO_2	+0.28	+0.94

Class II Programs

Once the chemical condition of an aqueous solution has been solved by a Class I calculation, modeling of chemical mass transfer into or out of the solution becomes possible. This can occur by 1) mixing or titration of a second solution into the first, 2) ion exchange reactions, or 3) solution/precipitation reactions. In natural systems, any mass transfer reaction is continuously dependent on its own progress and all other concomitant mass transfer processes. In mass transfer modeling each reaction progress is discretized to allow recalculation of the Class I speciation problem as information feedback to the continuing reaction path. Because the solution is altered by mass transfer processes, it is even possible for a stable mineral assemblage to be precipitated containing a phase which was undersaturated in the initial solution (Wolery, 1979).

In Class I computations, temperature, pH, Eh, and total chemical masses are treated as independent variables, leaving the species to be computed as the simultaneous solution of n equations in n unknowns. In mass transfer problems, Eh and pH also become unknowns, requiring two additional constraining equations. For pH, the condition of electrical neutrality is imposed. That is, the sum of all molal charges for species in solution (including H^+ ion) must be equal to zero. For Eh, the governing equation is the conservation of electrons. This requires quantitative bookkeeping of all electron transfers arising from redox reactions.

Generalizing the methods used in the Class II chemical programs, MIX2 (Plummer, et al., 1975), PHREEQE (Parkhurst, et al., 1980), and EQ3/6 (Wolery, 1979), the calculation sequences are as follows:

1. The Class I problem must first be solved (see calculation sequences in previous section) for the initial solution(s). Because later pH calculations are dependent on the solution electrical balance during mass transfer reactions, the initial solution(s) must be made electrically neutral by the addition of K^+ or Cl^- ion, or by adjusting the least reliable chemical constituent (possibly pH) from the reported laboratory analyses.
2. Based on mineral supersaturations and/or undersaturations, a mass transfer reaction step is calculated, subtracting and/or adding, respectively, to the appropriate aqueous chemical totals. Provisions are usually made for modeling the presence (closed system) or absence or removal (open system) of minerals in contact with the aqueous system.
3. The mass transfer step usually requires several iterations on the new solution pH and Eh, which are dependent on the total solution composition.

4. Each successive pH-Eh approximation requires the Class I speciation problem to be recalculated, involving several iterations on the mass balance-mass action equations as described earlier.
5. Once the new solution speciation equilibria and pH-Eh constraints have been satisfied, mineral saturation indices are redefined, and the next mass transfer step can be made.
6. Mass transfer steps continue until the new solution is in equilibrium with the mineral phases specified.

Because of the compounded iterative nature of the Class II calculations, optimization of numerical techniques and computing efficiency is a must. Test runs on MIX2, involving two endmember solutions (a geothermal water and a nonthermal water) and calcite precipitation from a mixture of the two, required over 1400 iterations of the central aqueous speciation model.

To test the reliability of this program, a geothermal sample from Steamboat Springs, Nevada, was collected and mixed with two laboratory standard, natural water sources in separate experiments (aqueous analyses for all three water samples are given in Appendix F). Under controlled temperature conditions, pH was measured at fixed mixing percentages between the geothermal sample and the selected nonthermal endmember. Chemical analyses of the endmember solutions were then entered and run on MIX2 to test the calculated pH against that measured in the laboratory. Results of the two experiments are shown in Figures 9.3 and 9.4. The correspondence between the theoretical and measured pH curves appears to be very good for both experiments. Because pH is one of the most crucial parameters to solution equilibria and Class II mass transfer problems, it can be concluded that the other theoretical results from such programs are at least reasonably accurate.

MIX2 does not handle redox or trace element reactions and can only calculate one mineral phase boundary at a time. PHREEQE (a derivative of MIX2 and WATEQF) and EQ3/6 are multiple-phase-boundary programs and are capable of computing redox and trace element species and mass transfers. Because of the numerical complexity of these programs, their use on small computers is not recommended. If the natural system complexity (in terms of predictive chemical monitoring) of a given geothermal development suggests the need for such methods, in-depth model development by an experienced geochemist would also be indicated.

Here, it should be emphasized that a computer program is not a model, but only a tool for modeling. The model is the information supplied to the program. PHREEQE, for example, is completely generalized. The user must supply all information regarding; 1) the chemistries of the initial solution(s), 2) if mixing or titration is to occur and in what relative volumes, 3) the speciation reactions important to the given system and all of their

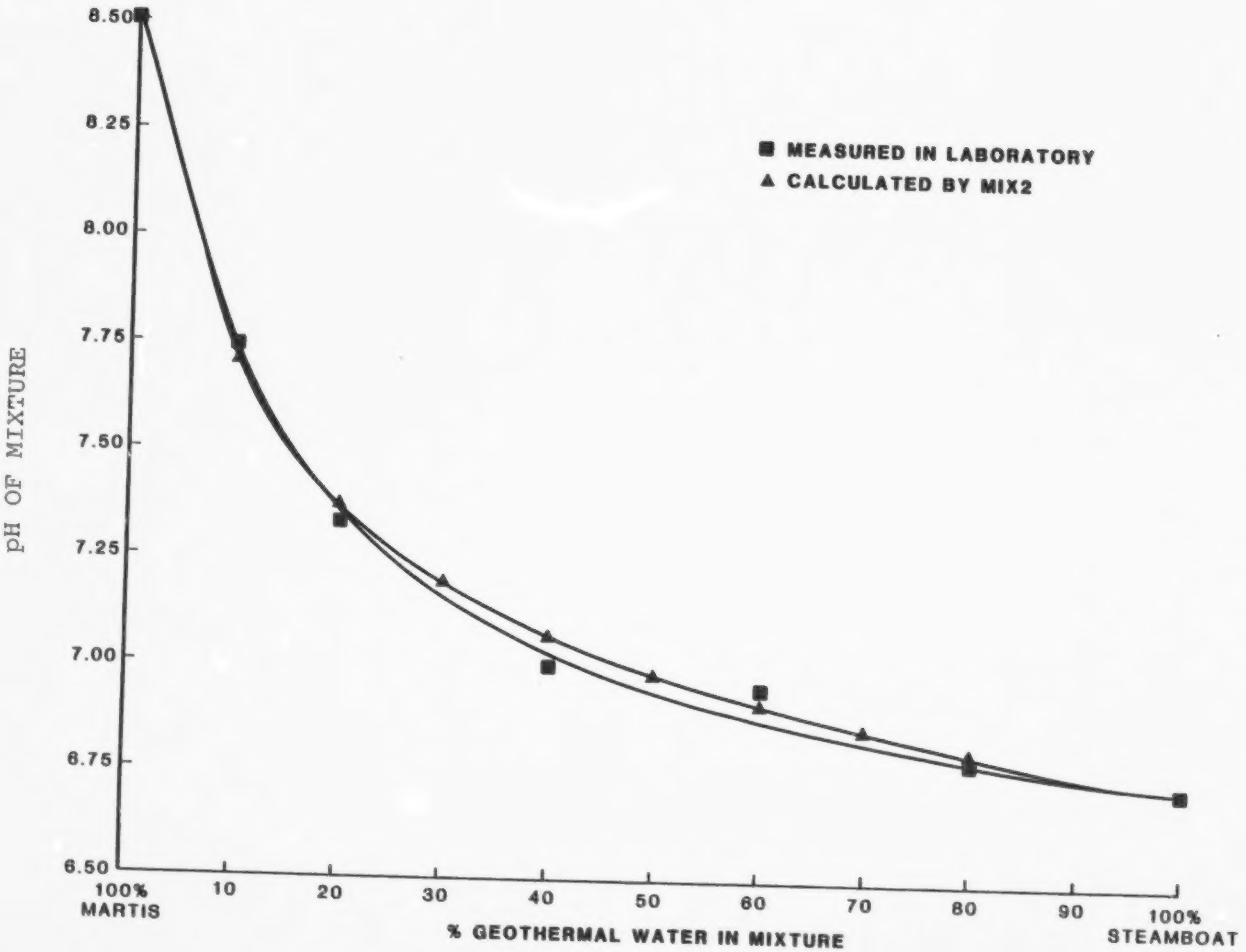

Figure 9.3 Computed and analytical pH-mixing curves (at 23.5°C) for endmember solutions from Martis Warm Springs, California, and Steamboat Springs, Nevada.

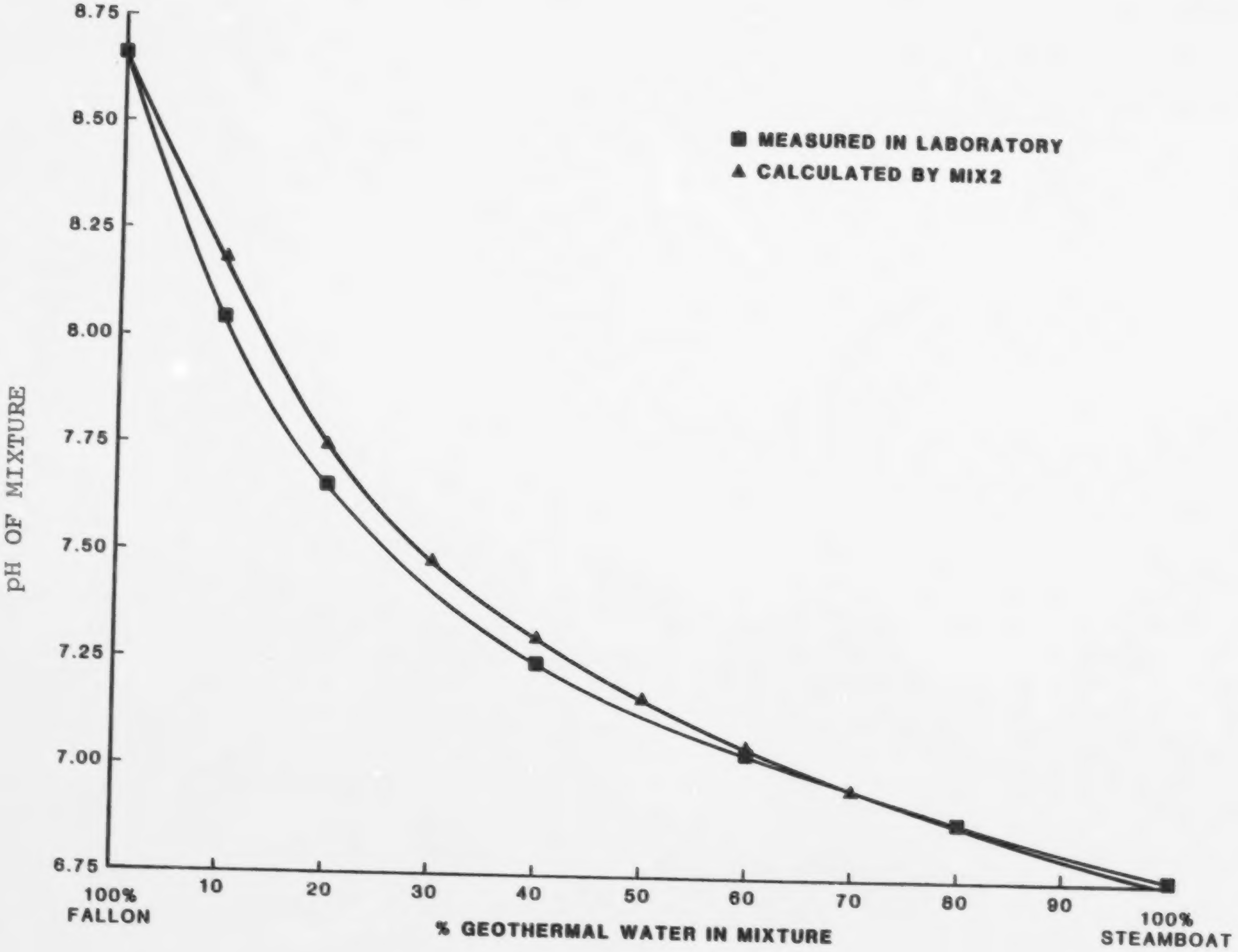

Figure 9.4 Calculated and analytical pH-mixing curves (at 23.5°C) for endmember solutions from Fallon, Nevada, wellwater and Steamboat Springs, Nevada.

thermochemical properties, 4) which minerals are available in the aquifer for dissolution and their thermochemical reaction properties, 5) reaction properties for all other minerals which may precipitate from the solution and whether they are to be removed from the system (open system) or not (closed system) upon precipitation, and 6) the specific thermochemical relationships to be used in adapting the numerous solution parameters to the temperature range of interest.

Of the programs evaluated, EQ3/6 may be the most readily applicable to geothermal problems because it's data systems already provide for calculation temperatures between 0-350°C. It also provides for calculations involving gas equilibria at pressures on the 1 atmosphere-steam saturation curve or a 500 bars constant pressure. The ultimate choice of a computer program, however, would be dependent upon the site-specific conditions and model requirements as determined by experienced professionals. Details of these programs are summarized in Appendix E.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A methodology has been developed for the selection of prioritized monitoring parameters based on their being either 1) essential to thermodynamic calculation for prediction of solution chemistry changes or 2) of interest as toxic or hazardous substances present in geothermal waters. These parameters are summarized in Table 9.2.

Because geothermal waters often contain a varity of major and minor substances at high ionic strength, large numbers of interdependent speciation reactions are possible where individual species activities are significantly lowered from their molal concentrations by electrostatic interferences as described by Debye-Huckel theory. A number of mass transfer reaction processes are applicable to geothermal aqueous system stresses which might arise from leaks or losses of fluids to nonthermal environments. The chemical tendency for specific mass transfer reactions to proceed is dependent on the activities of the correponding species. Specific mass transfer reaction pathways are continuously dependent on changing solution mass balance and speciation resulting from their own progress and the progress of other concomitant mass transfer reactions.

Because of the complexity of geothermal chemistry, prediction of the chemical affinity (saturation index) for a mass transfer reaction to proceed is best calculated by Class I type geochemical programs. This can provide useful insight as to which chemical parameters are most diagnostic of geothermal impact where changes in chemical mass may occur. Class I programs describe the thermodynamics of the solutions themselves as a function of pressure and temperature. Class II programs describe how these solutions interact with particular reservoirs. If actual estimates of mass transfer quantities are required, system modeling using Class II type geochemical programs is indicated.

For Class I systems analyses at one atmosphere pressure and temperatures below 100°C, WATEQF and WATEQ2 are applicable. WATEQ2 has much larger trace element capability than WATEQF. For Class I problems involving higher pressures and temperatures, SOLMNEQ is recommended. PHREEQE or EQ3/6 is recommended for Class II systems analyses. PHREEQE's thermodynamic data input is completely generalized and user dependent. That for EQ3/6 is already set for calculation reliability at higher temperatures and pressures. Choice of program type, the model supplied to the program, and interpretation of the modeling results require hydrologic and geochemical expertise.

FUTURE WORK

In-depth application of mass transfer and solute transport models to specific KGRA's is warranted. In solute transport modeling, conservation of the dissolved chemical mass is usually assumed, and attempts are made to refine hydrodynamic dispersion coefficients for solutes in order to make model results match those observed in the real world. In mass transfer modeling, solute masses are assumed to be nonconservative, and attempts are made to refine relative rates for mass transfer reactions in order to match natural solution/precipitation processes. Undoubtedly, in natural systems both processes are at work.

If the goal is to predict what water quality changes will occur (and when) at some point in a natural aquifer being intruded by a geothermal water, then attempts must be made to model these processes in natural systems where they are already occurring. This requires site-specific field data aquisition aimed expressly at the modeling objectives. Comprehensive and consistent field data provide the means for testing and calibrating such models, thereby improving their predictive capabilities.

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SECTION 10

MONITORING METHODOLOGY

INTRODUCTION

Monitoring for the impacts of geothermal energy development, conversion and waste disposal on groundwater systems is similar to groundwater monitoring for other purposes. Guidelines and methodology for developing groundwater monitoring programs are given by Everett (1980), Warner (1975), Weiss, et al. (1979) and Summers, et al. (1980) just to name a few of the many publications to appear on the subject over the last few years. The methodology presented here is based on the one presented by Weiss, et al. (1979). It has been refined to include the results of failure analysis and computer based solute transport and geochemical models.

The variation of the settings and human activities at or near potential geothermal energy areas precludes one monitoring plan which is applicable to all sites. The six-step methodology presented below is applicable to the release of geothermal fluid on the surface as well as below the surface. The method emphasizes groundwater impacts due to fluid injection into groundwater from a production or injection well. Inherent in the methodology is prediction of the possible impacts if a geothermal fluid release should occur. The six steps are:

1) Define baseline conditions including geology, hydrology water quality, geothermal system, plant design, existing surface and groundwater usage and other existing waste disposal systems.
2) Conduct failure analysis: compare the site characteristics to the results of industry-wide failure analysis to predict the most likely mode of fluid release.
3) Forecast aquifer conditions: predict travel times and chemical concentrations in the geothermal reservoir and overlying aquifers through the use of solute transport and geochemical models. Predict potential impacts, define limits of detection and use to design monitoring plan.
4) Select monitoring sites and techniques.

5) Design monitoring plan and alternatives, based on the above steps and legal and institutional constraints.
6) Implement monitoring plan and modify as experience dictates.

See Weiss, *et al*. (1979) and Everett (1980) for detailed discussions of Steps 1, 4, 5, and 6. The detailed backgrounds for Steps 2 and 3 have been presented in previous sections of this report. Brief summary discussions of each step are presented below. Section 11 will present illustrative examples of the application of this methodology.

DEFINE BASELINE CONDITIONS

Baseline conditions are those that exist prior to geothermal energy development. They may be natural or already altered by man. These conditions provide a basis for later comparison. In order to monitor for changes in groundwater conditions that may occur during geothermal energy development, the following baseline data must be established.

Chemical Characteristics of Waters

Chemical characteristics of all nongeothermal ground and surface waters and geothermal fluids need to be established, both in three dimensional distribution and temporal variations. Physical and chemical characteristics to be established include gross and trace element concentrations, stable isotope compositions and temperatures. Other liquid and solid waste disposal systems in the area should be characterized.

Sample collection and analysis procedures are presented in many references. They include: Brown, et al. (1970); Wood (1976); Reed (1975); Ellis, *et al*. (1968); Presser and Barnes (1974); EPA (1974); EPA (1976); EPA (1978); American Public Health Association (1977); Geonomics (1978); Ward (1978); Ward and Nielson (1978); Loftis and Ward (1979). These works detail most of the step-by-step procedures that should be followed in collecting and analyzing water and geothermal effluent samples. The documents by Shannon, *et al*. (1978) and Kindle and Woodruff (1981) are standard methods manuals specifically for sampling and analysis of geothermal fluids.

Geology and Hydrology

The distribution of aquifers and aquitards, including lithology and mineralogy, needs to be determined. Groundwater flow patterns, water levels and flow rates, including recharge and discharge areas and budgets, must be delineated. Aquifer and aquitard hydraulic properties need to be determined. Structural and stratigraphic features that may provide potential pollutant flow paths must be mapped.

Geothermal System

The geothermal system needs to be defined in as much detail as possible. The relationship between the geothermal and non-geothermal systems needs to be established. Information needed includes geometry of the geothermal reservoir, fluid temperature, pressure and chemistry, type of geothermal system, lithology and mineralogy of reservoir and recharge areas.

Site Design

Information on the type and size of project development is necessary. The volume of fluid to be extracted, number and location of production and injection wells, surface ponds and plant design need to be established. The chemical and physical changes to the geothermal fluid as it passes through the facility need to be estimated.

CONDUCT FAILURE ANALYSIS

Fault tree failure analysis should be utilized to determine possible points of failure and the relative probabilities of failure by a particular mechanism. Failures that occurred during development at the site should be evaluated to determine the cause of failure. This analysis will provide data on the most likely mechanisms by which future failures will occur. Once the mechanisms by which failures can occur are defined, the most likely piece of equipment to fail can be determined. The final step in this analysis would be to estimate the amount of fluid released for each type of failure (Summers, et al., 1980).

FORECAST AQUIFER CONDITIONS

The goal of this step is to determine the effects of the proposed production and waste disposal on the nongeothermal groundwater system. It serves three purposes: 1) prediction of movement of a pollutant in the aquifer systems and associated geochemical reactions; 2) location of monitoring sites and determination of monitoring parameters; and 3) definition of limits of detection. The baseline data and failure analysis provide the data necessary for this step. The key questions are: 1) can released geothermal fluids migrate to underground sources of drinking water and 2) are physical and chemical processes adequate to prevent significant levels of contamination.

The first step is to predict potential impacts of a geothermal fluid release on present and future groundwater users. An attempt is made to determine when and if a pollutant would reach a user and what the pollutant would be. Geochemical models interact the geothermal fluid with nongeothermal groundwaters and nongeothermal aquifer mineralogies to determine the resultant chemistry or trends in the resulting chemistry.

Using the above information, the best locations for monitoring sites and the best chemical constituents to monitor can be determined. The information can also be used to determine limits of detection for various chemical constituents. Through the use of the models, the possible effects of alternate development scenarios can be evaluated.

SELECT MONITORING SITES AND TECHNIQUES

Groundwater monitoring should take place at the geothermal site as well as in the surrounding area. Most of the monitoring techniques, except surface geophysics and surface water and spring samples, require the use of wells. The various monitoring techniques have been discussed in Section 7. Each of these techniques and types of monitoring well must be evaluated in light of results of forecasting aquifer conditions. Monitoring wells are of four types (Weiss, _et al_., 1980 and Warner, 1975):

1) nondischarging wells constructed into the receiving aquifer,
2) nondischarging wells constructed into or just above the confining unit,
3) wells constructed above the confining unit (usable aquifers) and,
4) injection wells.

DESIGN MONITORING PLAN AND ALTERNATIVES

Based on the previous four steps, a site specific monitoring plan is developed, along with alternatives. Components of the plan are (Weiss, et al., 1980):

1) spatial distribution of sample points and sampling frequency,
2) applicable monitoring techniques,
3) chemical and physical parameters,
4) legal and institutional specifications, and
5) cost versus confidence.

IMPLEMENT MONITORING PLAN

Implementation of the monitoring plan involves data collection and interpretation and review and modification of the plan. Data collection is only the first step. Methods need to be devised for data storage and retrieval systems that are easy to use. The data then need to be analyzed and interpreted. Periodically the monitoring program should be reviewed and modified to meet the needs of the site.

SUMMARY

In selecting a monitoring plan, it should be kept in mind that the most effective way to detect a leak in the system will be to continuously monitor physical and chemical parameters on the production and injection wells. Properly placed monitoring wells will serve to evaluate the impact of a leak on the underground source of drinking water and may detect a small slow leak. The effectiveness of monitoring wells may be limited due to the fact that in most geothermal areas (as pointed out in Section 11), the underground source of drinking water have been impacted by the geothermal fluid naturally.

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SECTION 11

ILLUSTRATIVE EXAMPLES

Section 10 summarized a six-step methodology for designing site specific groundwater monitoring plans for geothermal energy development, conversion and waste disposal. Application of these steps should result in an assessment of potential groundwater impacts and a monitoring design to detect changes in groundwater quality.

Three examples of the application of the first four steps of the monitoring methodology are presented below. They are monitoring at Raft River KGRA in Idaho, and hypothetical examples of leakage from a lagoon and of contaminant plume tracking and interception. The baseline conditions for Raft River are not as well described as they should be since all of the data used here have been drawn from the literature.

RAFT RIVER, IDAHO

Baseline Data

The Raft River KGRA covers an area of 11,750 ha in the Raft River Valley of southern Idaho (Figure 11.1). Major development at the site has been through a cooperative venture between the U.S. Department of Energy, the Raft River Rural Electric Cooperative and the Idaho Department of Water Resources. The aim of this cooperative venture is to demonstrate the technical feasibility of power generation from a moderate temperature (150°C) geothermal resource.

Geology--

The Raft River Valley is a north-south trending structural depression which is bounded by fault-block mountains on the east, west and south (Anderson, 1931). The mountains consist of Tertiary volcanic and sedimentary rocks, Paleozoic limestones and

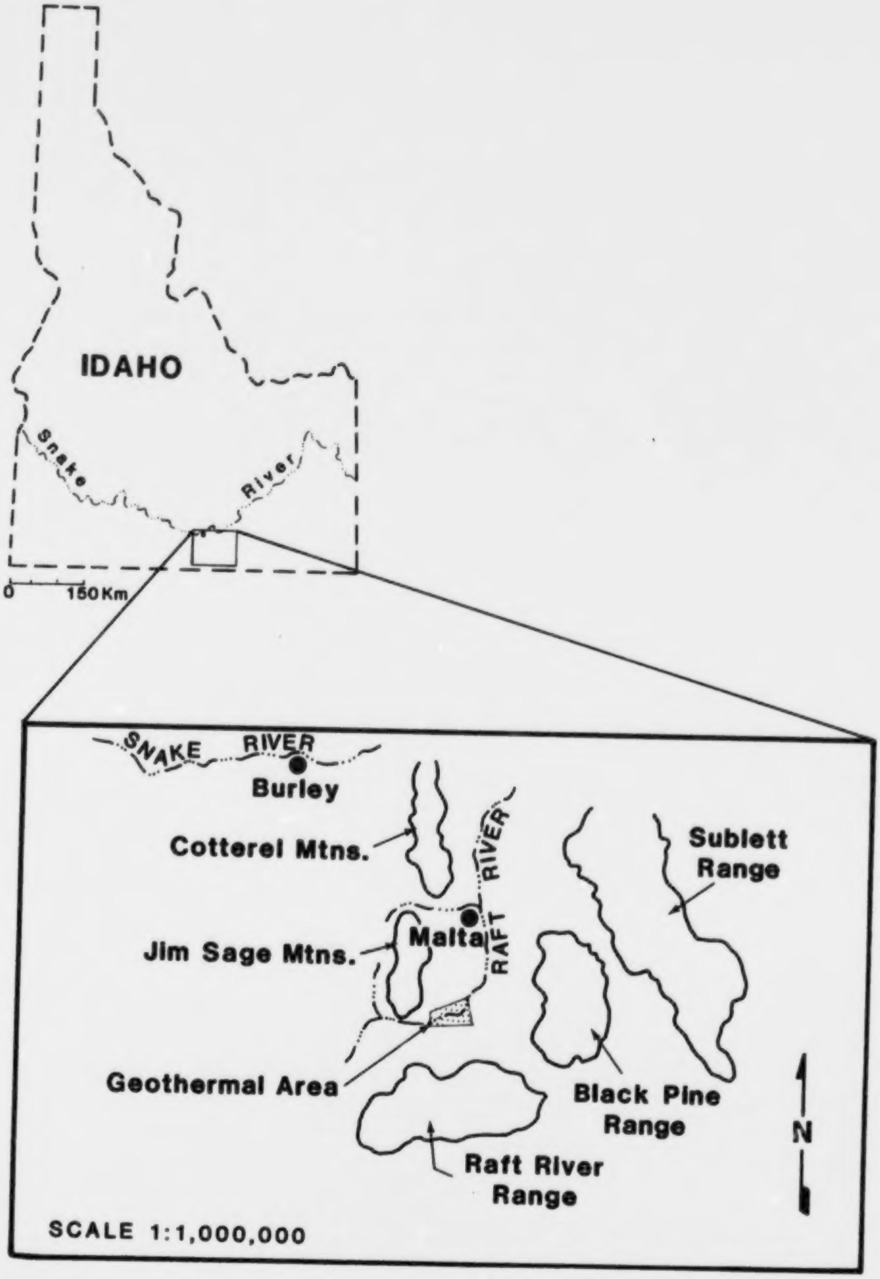

IDAHO
Snake River
0
150Km
SNAKE RIVER
Burley
Cotterel Mtns.
RAFT RIVER
Sublett Range
Malta
Jim Sage Mtns.
Geothermal Area
Black Pine Range
Raft River Range
N
SCALE 1:1,000,000

Figure 11.1 Location map of the Raft River KGRA

sandstones and Precambrian adamellite (Overton, et al., 1979). The basement rock in the area consists of the Precambrian formations. This is overlain by the valley fill sediments of the Salt Lake Formation. The Salt Lake Formation forms the majority of the valley fill and consists of unconsolidated quartzose silts and sands, tuff, quartzite and rhyolite gravels. The Pleistocene Raft Formation overlies the Salt Lake Formation and consists of sand, gravel, silt and clay. The valley fill sediments are approximately 1200 m thick and are difficult to correlate in the upper 300 m.

A system of normal faults in the area is believed to control the movement of geothermal fluids particularly in the Salt Lake Formation. A shallow magma body is interpreted as the heat source for the geothermal system.

Hydrology--

The Raft River Valley is considered a high desert area which receives 25 cm annual precipitation in the valley and over 80 cm in the surrounding mountains. The main surface drainage in the valley is the Raft River. The river flows north-east and drains into the Snake River. During the summer irrigation season the total flow of the Raft River is diverted for irrigation. The river is primarily a losing stream, providing recharge to the shallow groundwater system (Nace, et al., 1961).

Groundwater withdrawals for irrigation occur throughout the Raft River Valley. Water levels have declined as much as 30 m, prompting the state of Idaho to close the basin in 1963 to further appropriation of groundwater. Aquifers occur in the Salt Lake and Raft Formations in both confined and unconfined conditions (Walker, et al., 1970). The general direction of groundwater movement is towards the north (Mundorff and Sisco, 1963). Upward leakage from deeper aquifers supplies, in part, recharge to the shallower aquifers (Nichols, 1979). Within the KGRA, irrigation and shallow monitoring wells show chemical and thermal evidence of upward leakage from the geothermal reservoir. Water quality data for both the geothermal and non-geothermal aquifers are given in Table 11.1.

Plant Design--

Under the direction of DOE a 5 MW binary cycle power plant was operated during early 1982 to demonstrate the feasibility of power generation from a moderate temperature reservoir. The power plant required 150 l/s of 140°C fluid which will be produced from wells RRGE-1, RRGE-2 and RRGE-3 (Spencer and Callan, 1980).

TABLE 11.1 REPRESENTATIVE ANALYSES OF WATER FROM SELECTED WELLS IN THE RAFT RIVER BASIN

	RRGE-1 (mg/1)	RRGE-2 (mg/1)	RRGE-3 (mg/1)	RRGI-6 (mg/1)	MW-1 (mg/1)	MW-3 (mg/1)	MW-4 (mg/1)	MW-5 (mg/1)	MW-6 (mg/1)	15S24E27daa1 (mg/1)	15S26E23abd1 (mg/1)
Ca	56	35	178	214	215	170	217	107	230	107	107
K	34	38	105	32	30	54	25	14	56	5.9	23
Li	1.6	1.1	3.1	5.1	3.7	3.1	3.2	0.3	3.1	0.1	2.0
Mg	0.6	0.13	0.5	1.4	0.4	3.4	3.2	25	2.4	27	5.5
Na	472	441	1194	2100	2220	1350	1400	230	1570	71	809
SiO_2	184	156	165	94	80	60	76	29	87	46	65
Cl^-	832	681	2260	3640	3680	2400	2420	717	2930	197	1303
F^-	5.6	8.7	4.9	7.1	3.4	5.4	4.9	0.6	4.9	0.4	4.9
HCO_3	41	90	44	73	25	46	41	101	44	182	123
SO_4	36	53	60	60	66	48	51	27	63	86	90
pH	7.3	7.6	7.2	7.3	7.9	7.6	7.8	7.8	7.7	7.1	--
TDS	1650	1290	4100	6380	6270	4300	4370	1229	4820	720	2400
Temp (°C)	141	144	149	71	--	71	98	29	44	13	29
Depth (m)	1520	1994	1804	1176	399	152	305	152	335	105	110

(From Spencer and Callan, 1980.)

Approximately 120 l/s of spent geothermal fluid was injected through wells RRGI-6 and RRGI-7 with the remainder being lost through evaporation in the cooling system. All pipelines at the KGRA are made of asbestos-cement. The pipes are buried at least 0.6 m and are covered with 25 mm of spray insulation (Blake, 1978).

The plant was closed permanently in 1982 due to the high cost of operation and technical design problems which included: the inability of the asbestos-cement pipelines to absorb pressure or thermal shocks without cracking, the unavailability of fresh cooling water requiring the use of spent geothermal fluid as cooling water initiating many chemical complications, and the use of carbon steel as the condenser tubing material, which limited component lifetime due to corrosion attack.

Failure Analysis--

The main concern at the Raft River KGRA will be that injection is done at great enough depths to protect the shallow aquifer system.

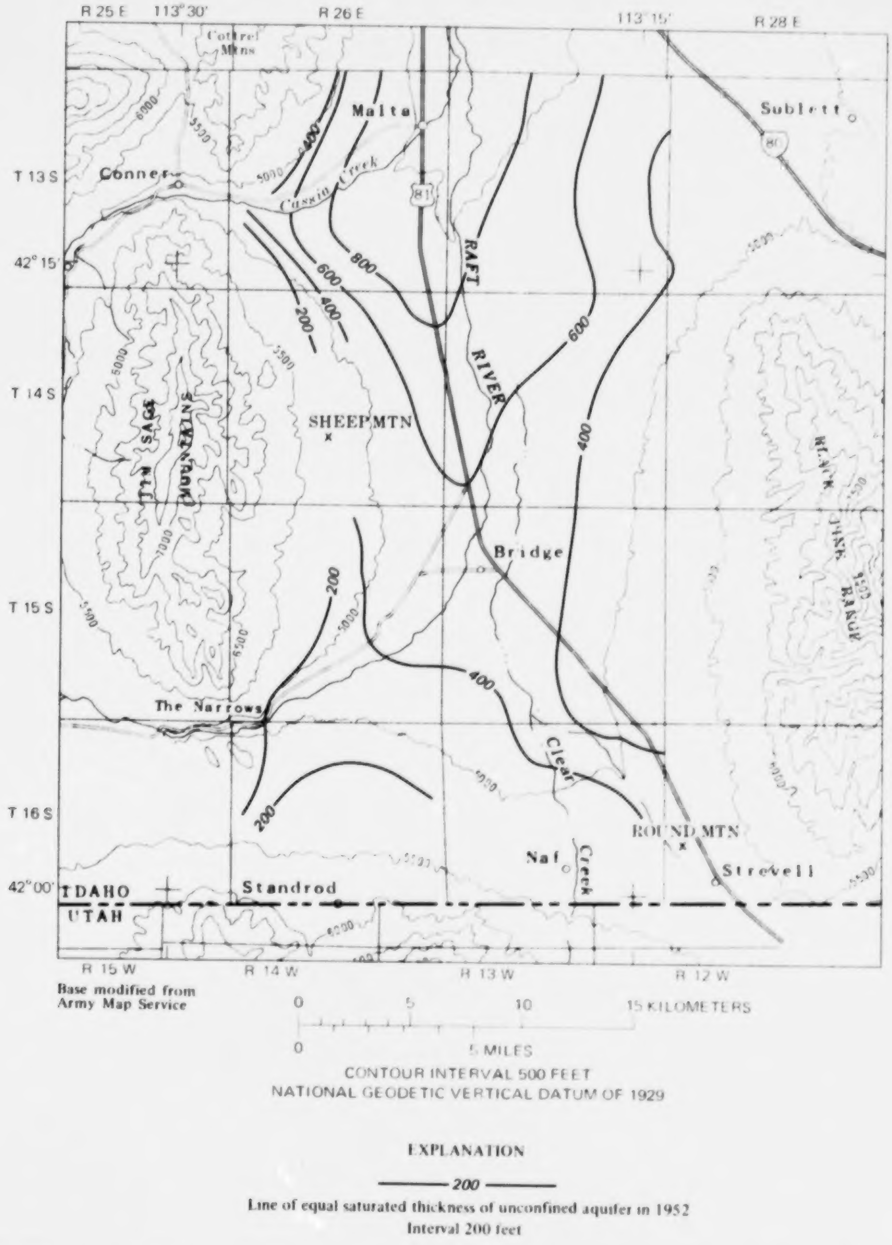
Forecast Aquifer Conditions

Contaminant Transport--

Because the model POLLUTE uses English units this section of the report uses English units instead of metric.

Groundwater in the Raft River basin occurs both in confined and unconfined aquifers in the Salt Lake formation, the Raft River formation, and in the surface alluvium. However, in this study, the surface alluvium is the only aquifer considered since it is the most heavily used groundwater supply. Nichols (1979) states that the saturated thickness of the unconfined aquifer ranges from less than 200 feet (ft) to greater than 800 ft (Figure 11.2), with a hydraulic gradient of approximately 0.0055 (Figure 11.3). Similarly, the transmissivity ranges from less than 1000 to greater than 7000 ft^2/day (Figure 11.4), and the specific yield ranges from 0.10 to 0.18 (Figure 11.5). Although porosity is generally larger than the specific yield (Figure 11.6), in this study they are assumed to be equal (due to insufficient porosity data). Considering that aquifer porosity is inversely related to solute travel velocity, actual arrival times of the geothermal fluid at a pumping well may be later than the arrival times predicted by POLLUTE.

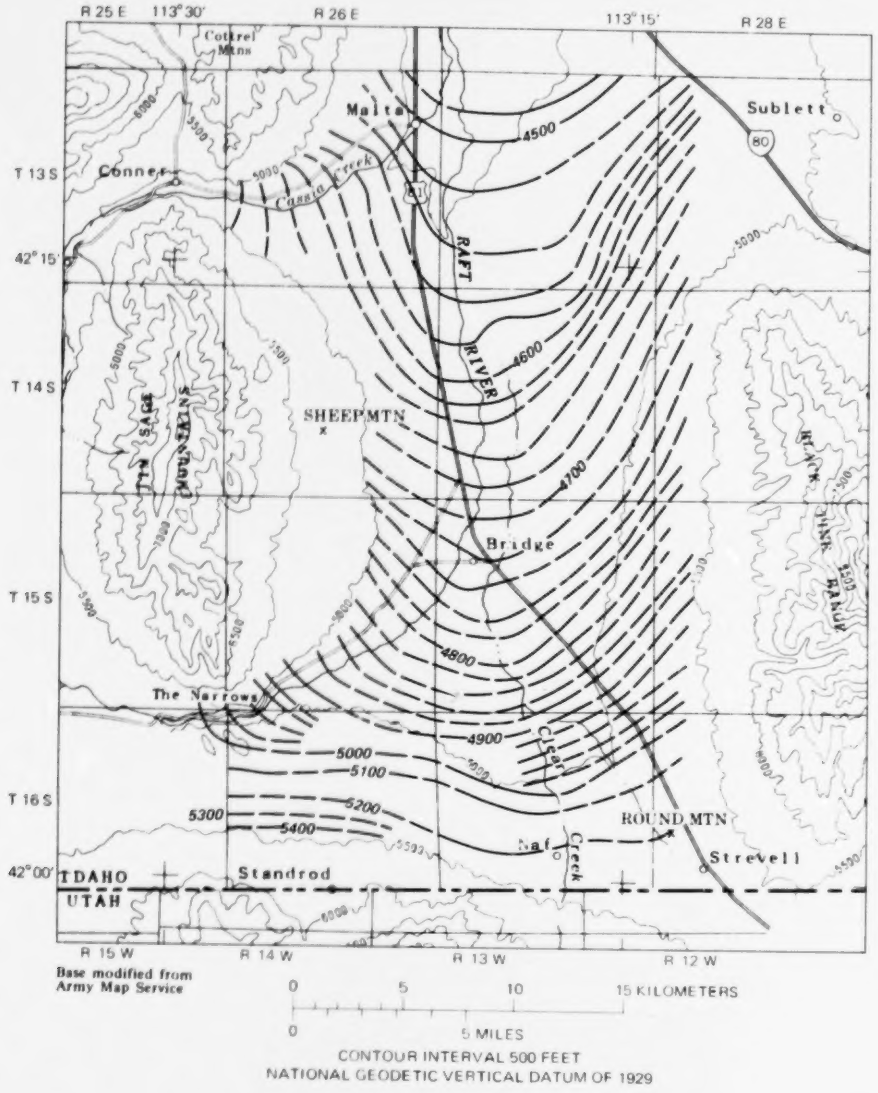
GEOHYDROLOGY OF THE SHALLOW GROUND-WATER SYSTEM



R 25 E
113°30'
R 26 E
113°15'
R 28 E
Cotterel Mtns
Malta
Sublett
80
Conner
Cassia Creek
81
T 13 S
42°15'
T 14 S
T 15 S
T 16 S
42°00'
RAFT RIVER
SHEEP MTN
SUBLETT RANGE
BLACK PINE RANGE
Bridge
The Narrows
Clear Creek
ROUND MTN
Naf
Naf Creek
Strevell
Standrod
IDAHO
UTAH
800
600
400
200
5000
5500
6000
6500
R 15 W
R 14 W
R 13 W
R 12 W
Base modified from Army Map Service
0
5
10
15 KILOMETERS
0
5 MILES
CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929
EXPLANATION
200
Line of equal saturated thickness of unconfined aquifer in 1952
Interval 200 feet

Figure 11.2 Saturated thickness of the unconfined surface aquifer (from Nichols, 1979)

GEOHYDROLOGY OF THE SHALLOW GROUND-WATER SYSTEM

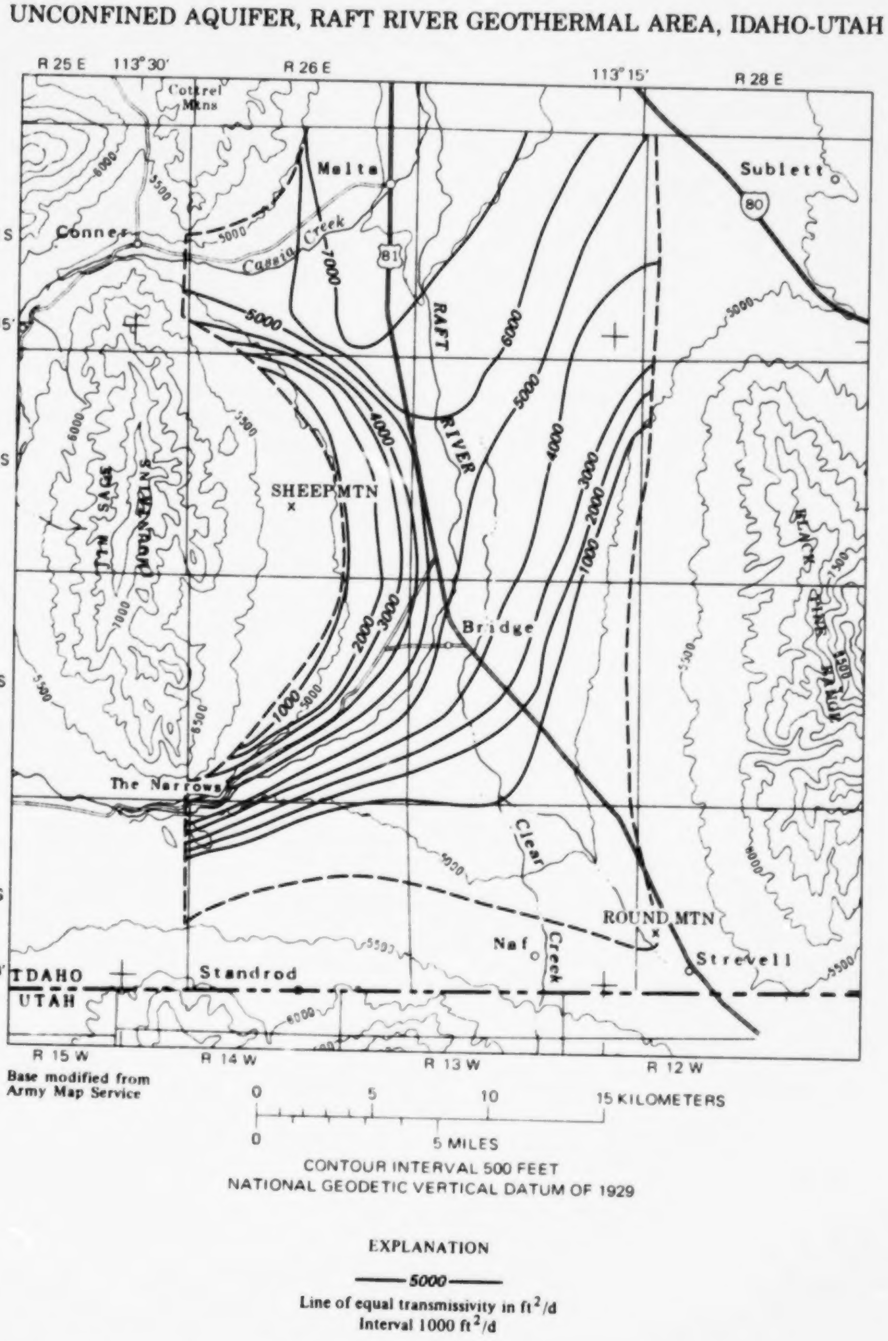

R 25 E
113°30'
R 26 E
113°15'
R 28 E
Cotterel Mtns
Malta
Sublett
80
4500
T 13 S
Conner
5000
Cassia Creek
81
RAFT
RIVER
42°15'
5000
4600
T 14 S
SHEEP MTN
SAGE MOUNTAIN
BLACK PINE RANGE
4700
Bridge
T 15 S
4800
The Narrows
4900
5000
5100
Clear
T 16 S
5300
5200
5400
ROUND MTN
Naf
Creek
Strevell
42°00'
IDAHO
UTAH
Standrod
R 15 W
R 14 W
R 13 W
R 12 W
Base modified from Army Map Service
0
5
10
15 KILOMETERS
0
5 MILES
CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

——— 5000 — — —

Line of equal water level altitude. Dashed where assumed.
Datum is mean sea level
Interval 20 feet and 100 feet
(modified after Nace and others, 1961)

Figure 11.3 Uniform flow potential in unconfined surface aquifer (from Nichols, 1979)


UNCONFINED AQUIFER, RAFT RIVER GEOTHERMAL AREA, IDAHO-UTAH
R 25 E
113°30′
R 26 E
113°15′
R 28 E
Cottrel Mtns
Malta
Sublett
80
T 13 S
Conner
Cassia Creek
81
42°15′
RAFT
RIVER
T 14 S
SHEEP MTN
SAGE
HILL
BLACK PINE RANGE
T 15 S
Bridge
The Narrows
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Creek
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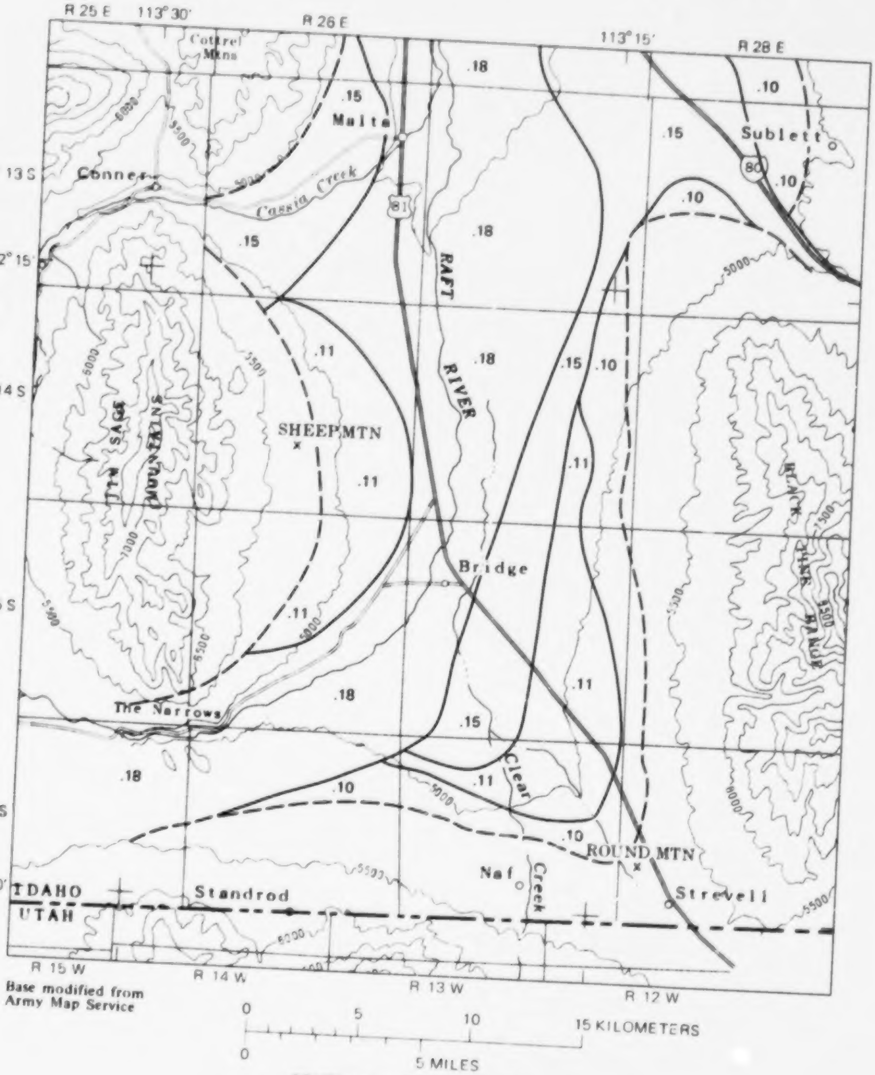
IDAHO
UTAH
Standrod
R 15 W
R 14 W
R 13 W
R 12 W
1000
2000
3000
4000
5000
6000
7000
5500
Base modified from Army Map Service
0
5
10
15 KILOMETERS
0
5 MILES
CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929
EXPLANATION
5000
Line of equal transmissivity in ft²/d
Interval 1000 ft²/d

Figure 11.4 Transmissivity of the unconfined surface aquifer (from Nichols, 1979)


R 25 E
113°30'
R 26 E
113°15'
R 28 E
Cotterel Mtns
Malta
Sublett
Conner
Cassia Creek
81
80
RAFT RIVER
T 13 S
42°15'
T 14 S
T 15 S
T 16 S
42°00'
SUBLETT RANGE
SHEEP MTN
Bridge
The Narrows
Clear Creek
Naf
ROUND MTN
Strevell
Standrod
IDAHO
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BLACK PINE RANGE
.18
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5
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15 KILOMETERS
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5 MILES

Base modified from Army Map Service

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

– – – – – –
Aquifer boundary of Walker and others, 1970
(after Walker and others, 1970)

Figure 11.5 Specific yield of the unconfined surface aquifer (from Nichols, 1979)

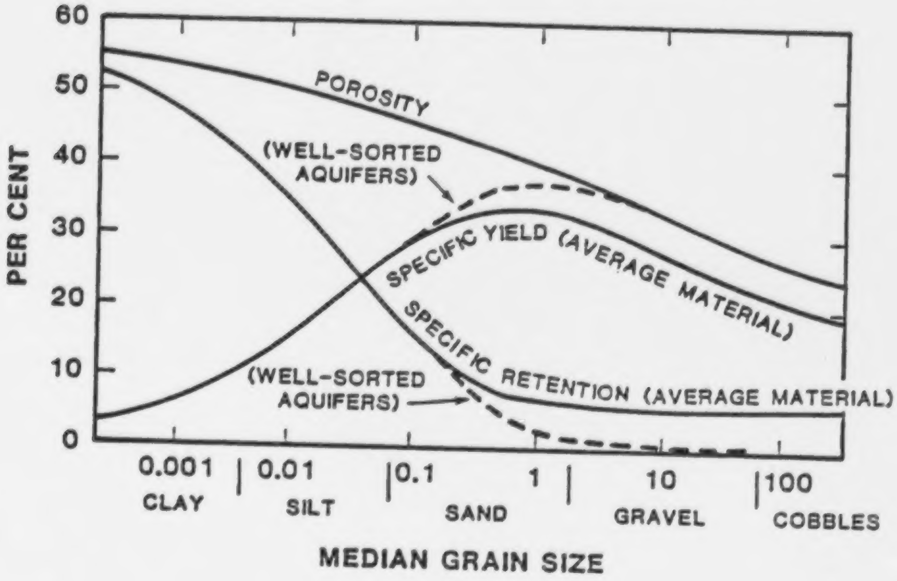


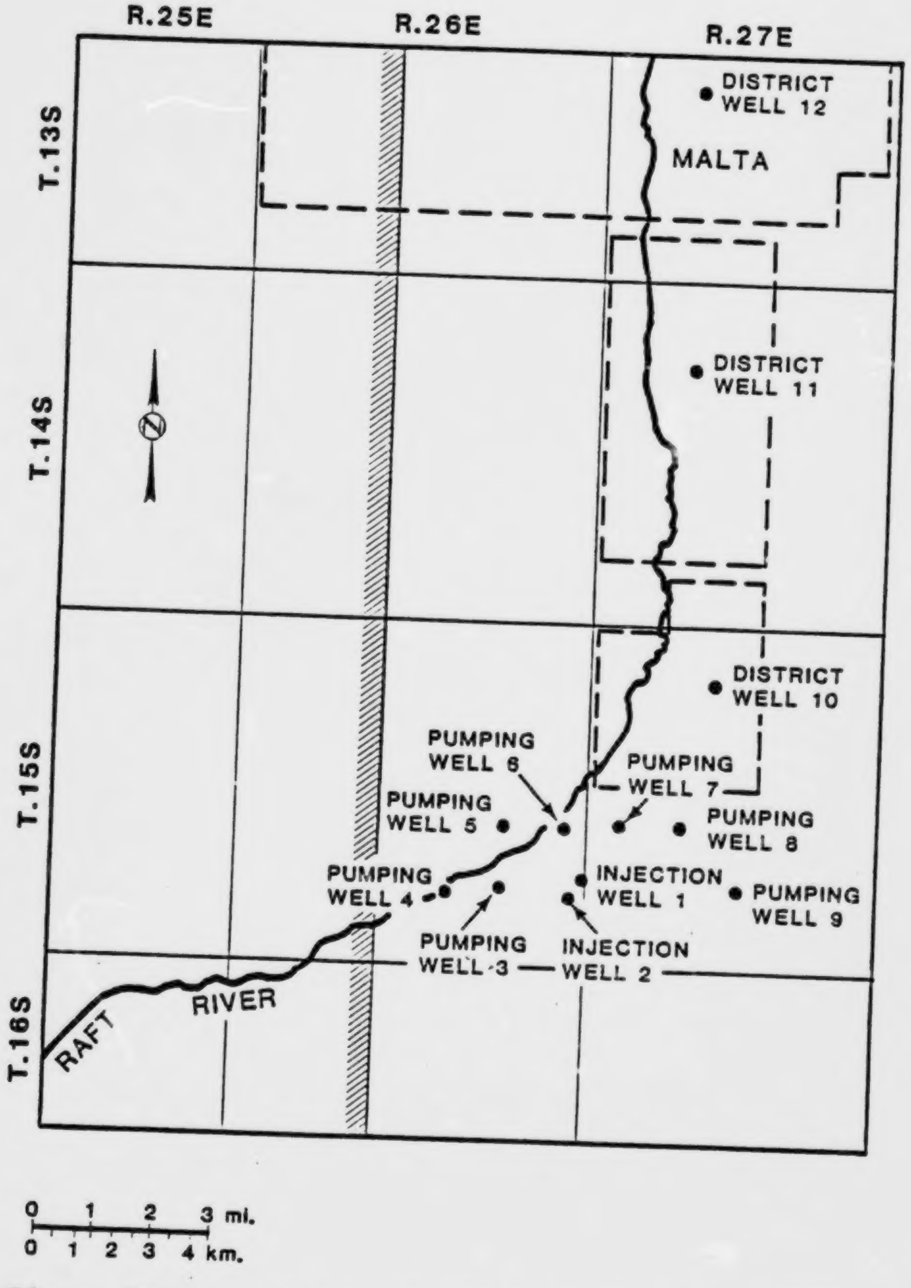
Figure 11.6 Relation between porosity, specific yield, and specific retention with varying grain size.

Since POLLUTE requires single values for porosity, hydraulic conductivity, saturated thickness, uniform flow gradient, and uniform flow direction, an approximate average or best estimate for each parameter in the vicinity of the injection wells was used. Saturated thickness was considered to be 500 feet, hydraulic conductivity was 10 feet/day, porosity was 0.18, and the uniform flow gradient was considered to be from the south at 0.0055. These values were derived from Figures 11.2 through 11.5. (Note: The specific yield values of Figure 11.5 were considered equivalent to porosity. However, as illustrated in Figure 11.6, specific yield is always less than or equal to porosity. Therefore, the equivalence made here will result in conservative (quicker) travel times.

Four and a half kilometers west of the injection wells and parallel to the uniform flow field, an impermeable image well boundary is created by POLLUTE to simulate the aquifer discontinuity caused by the Jim Sage Mountains (refer to Figure 11.7). The Raft River, an intermittent stream that cuts across the KGRA, is not considered to be a significant hydrologic feature. This assumption, also made during a transient head simulation study of the same area (Nichols, 1979), was a simplifying assumption made on the grounds that flow in the Raft River is directly dependent upon the extent of groundwater used. When substantial amounts of groundwater are pumped for agriculture during the summer months, the river runs dry.

The location of the two injection wells was outlined by Miller and Prestwich (1979). The locations and projected 1974 discharges of the various pumping areas were tabulated by Nichols (1979). Nichols, however, located this data by township, range, and section only. Since each section is a square mile, the exact location of any well within that section is not defined. For the purposes of this example, all pumping areas were located at the center of their respective section, and their pumping rates were considered constant. Since POLLUTE is programmed to only account for up to twenty wells, many of the pumping areas were grouped together to form "district" wells. Each district well was located near the center of its well group and had a discharge equal to the sum of all the individual well discharges within that group. Three of these district wells were created, the largest encompassing the town of Malta with the two smaller ones extending south to the injection area (Figure 11.7).

POLLUTE was used in the simulation of three leakage scenarios. The three scenarios attempted to delineate the worst possible situations in which the 8.4×10^7 feet^3/year planned injection rate for each of the two injection wells (Susan Petty, 1981, personal communications, EG&G Idaho) would leak into the unconfined surface aquifer. The first two scenarios had only one of the two injection wells leaking into the aquifer. The third scenario had both wells leaking.


R.25E
R.26E
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N
DISTRICT WELL 12
MALTA
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DISTRICT WELL 10
PUMPING WELL 6
PUMPING WELL 7
PUMPING WELL 5
PUMPING WELL 8
PUMPING WELL 4
INJECTION WELL 1
PUMPING WELL 9
PUMPING WELL 3
INJECTION WELL 2
RAFT RIVER
0 1 2 3 mi.
0 1 2 3 4 km.

Figure 11.7 Location of wells in the Raft River study area. Hachured line indicates impermeable image well boundary. Dashed line delineates District Well domains.

The aquifer in all scenarios was considered homogeneous and isotropic. The injected geothermal fluid was considered nondispersive, nonreactive, nonadsorptive, and had the same density as the ambient groundwater. Other simplifying assumptions include strictly horizontal flow and no leakage from (or to) deeper aquifers. These simplifying assumptions, as well as the ones mentioned earlier, may not be accurate for the entire study area and may cause the resulting simulations to be somewhat in error.

In the first simulation, injection well 1 leaked into the aquifer at a rate of 8.4 x 10^7 feet^3/year. As seen from Figures 11.8a and 11.8b most of the geothermal fluid migrated to pumping well 6 with some fluid continuing on to district pumping well 11. Pumping well 6 represents an irrigation area approximately one mile north of the injection area. District well 11 represents an agricultural and municipal region just south of Malta. The resulting well flow distribution (Figures 11.8c and 11.8d) indicates that substantial contamination will occur at pumping well 6 approximately 10.4 years after commencement of leakage. Slight contamination of district well 11 will occur 224 years later.

In the second simulation, injection well 2 leaked into the aquifer, also at a rate of 8.4 x 10^7 feet^3/year. Figure 11.9 shows all the contaminant terminating at pumping well 6. The resulting well flow distribution (Figure 11.9b) indicates contaminant interception at well 6 occurring approximately 11.2 years after the onset of leakage.

The third scenario can be considered the worst case situation where both injection wells are leaking a total of 1.68 x 10^8 feet^3/year into the aquifer. Figures 11.10a and 11.10b show that contaminant from both wells terminates at pumping well 6. Some contaminant from injection well 1 will also terminate at district well 11. As per the well flow distributions (Figures 11.10c, 11.10d and 11.10e), contaminant interception at well 6 will be substantial and occur at 9.8 years after the start of leakage whereas contaminant interception at district well 11 will be slight and occur 197.4 years later.

These simulations indicate that pumping well 6 will be the primary interceptor of geothermal fluid leaking from either injection well. All fluid leaking from injection well 2, and most of the fluid leaking from injection well 1 will terminate at well 6 less than 10 years after leakage begins. Some of the municipal and agricultural wells in the area just south of Malta (district well 11) could also expect to intercept some contaminant in the distant future provided injection well 1 starts leaking. As previously stated, these simulations are subject to many simplifying assumptions which may be reflected in the simulation accuracy.

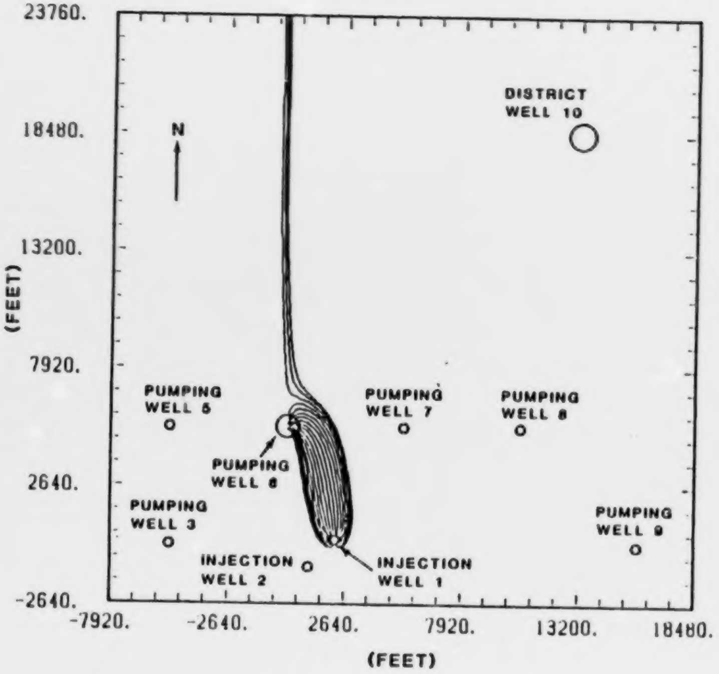


Figure 11.8a Simulation of leakage from Injection Well 1.

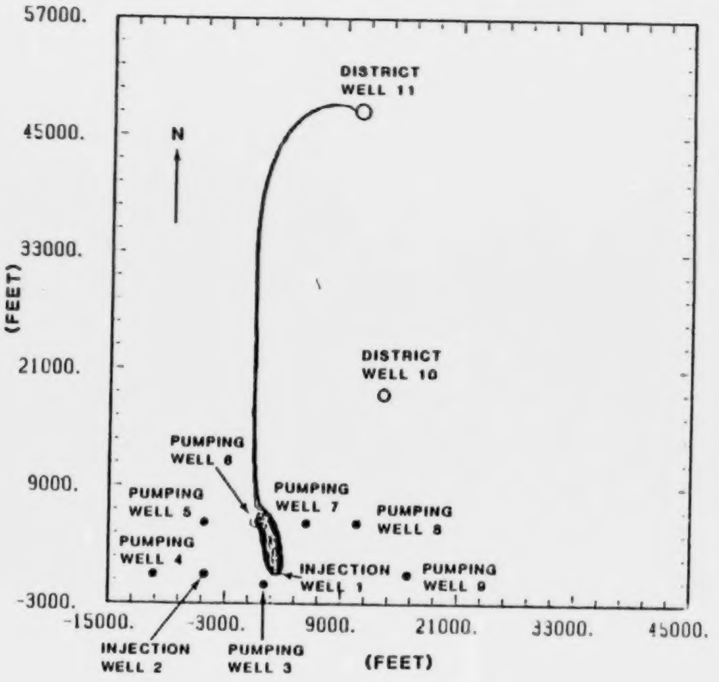


Figure 11.8b Simulation of leakage from Injection Well 1.

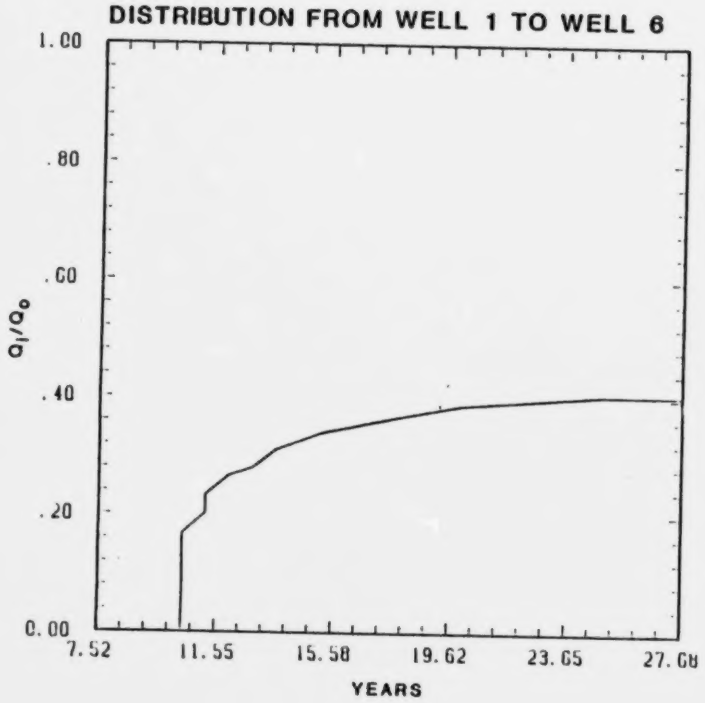


Figure 11.8c Well flow distribution during leakage from Injection Well 1.

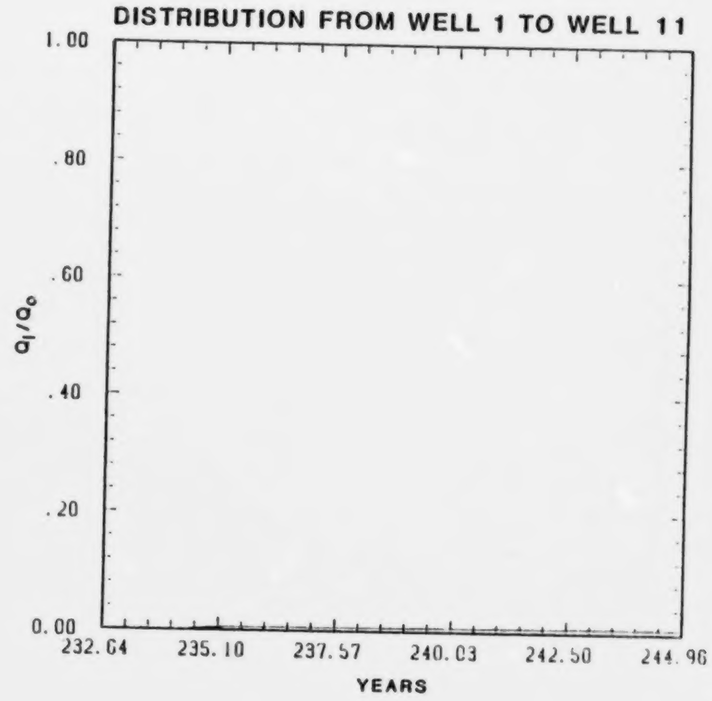
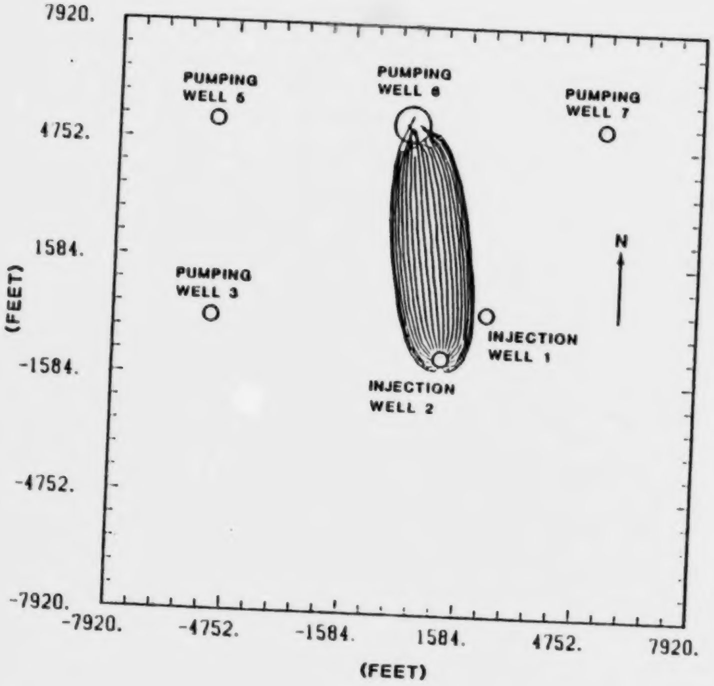


Figure 11.8d Well flow distribution during leakage from Injection Well 1.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PUMPING WELL 7
PUMPING WELL 3
INJECTION WELL 1
INJECTION WELL 2
N

Figure 11.9a Simulation of leakage from Injection Well 2.

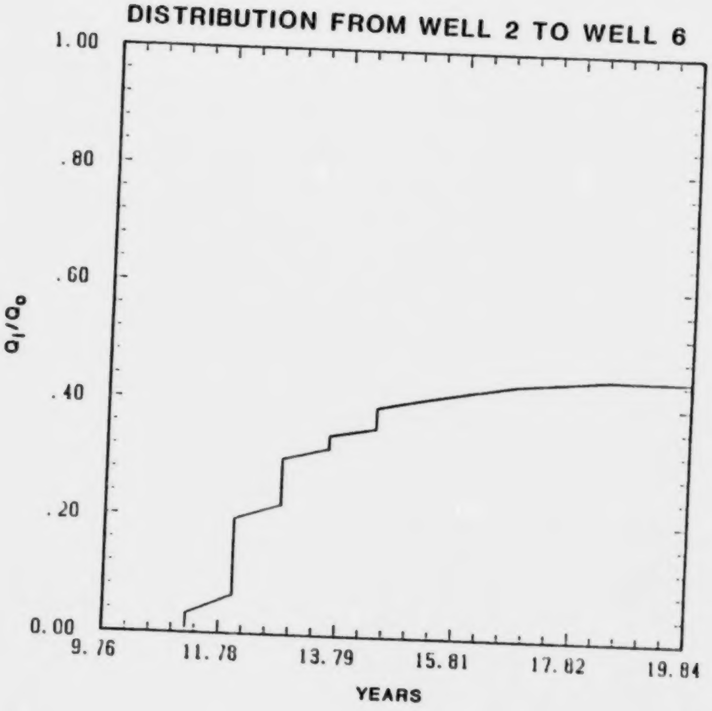


Figure 11.9b Well flow distribution during leakage from Injection Well 2.

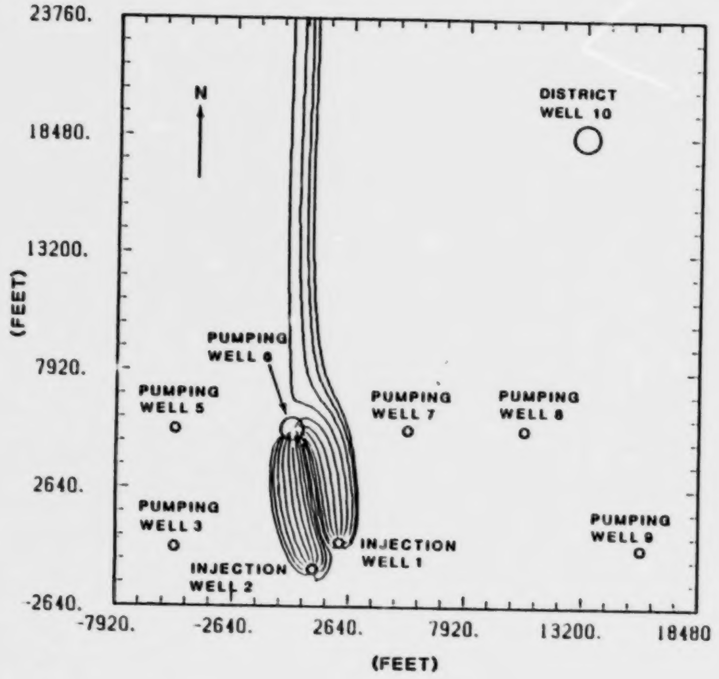


Figure 11.10a Simulation of leakage from both injection wells.

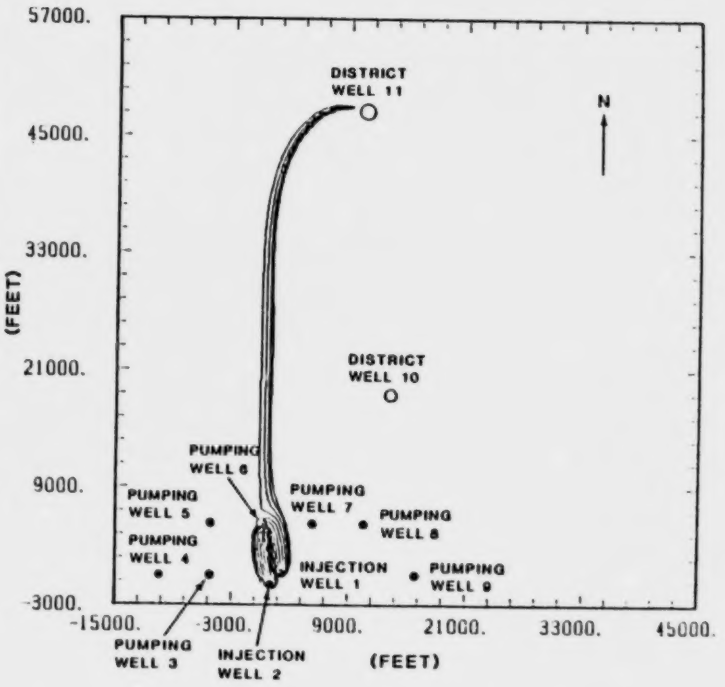


Figure 11.10b Simulation of leakage from both injection wells.

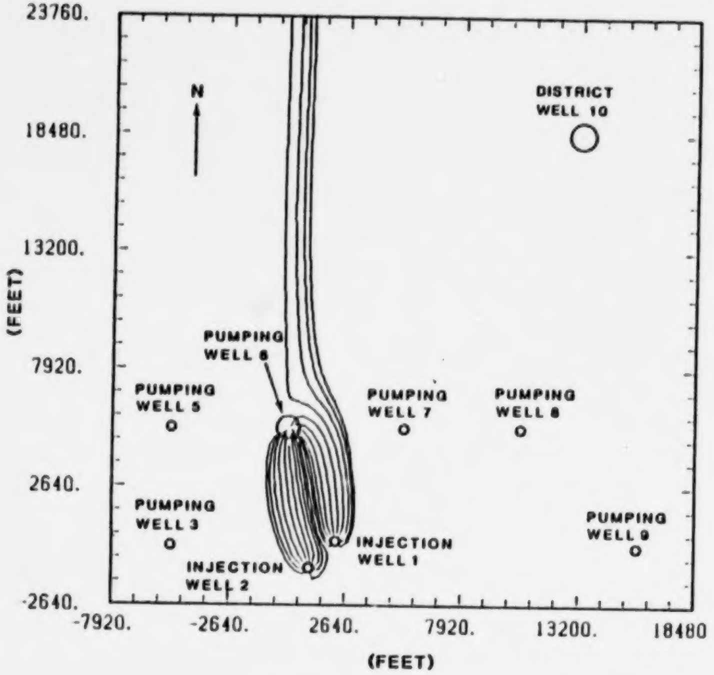


Figure 11.10a Simulation of leakage from both injection wells.

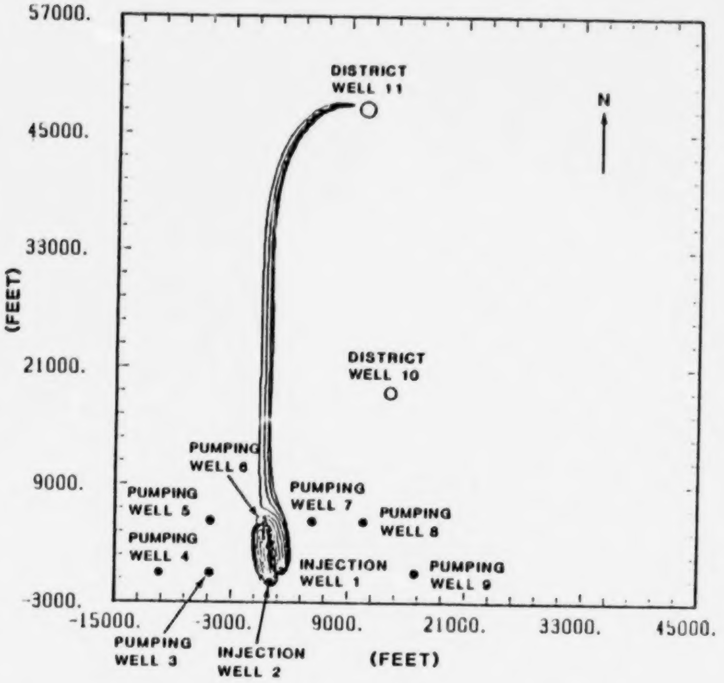


Figure 11.10b Simulation of leakage from both injection wells.

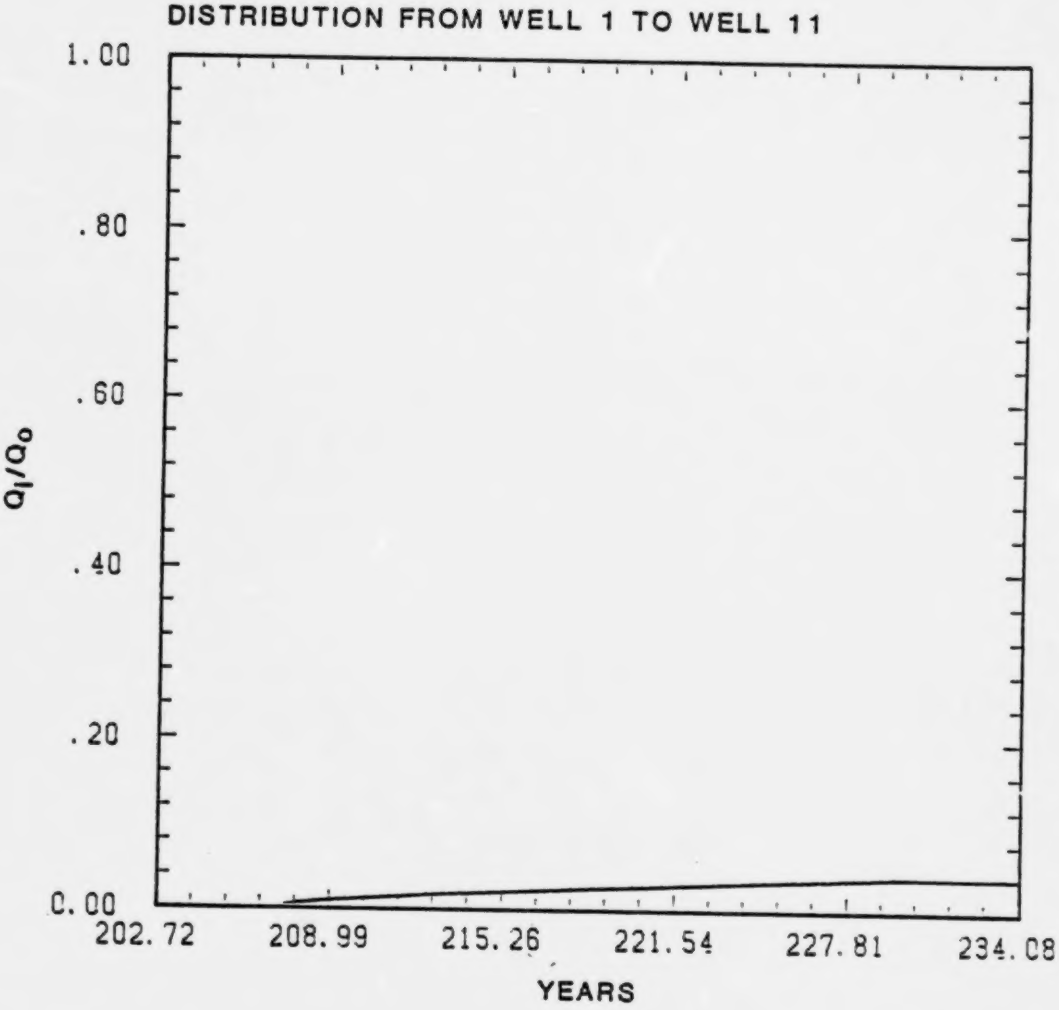


Figure 11.10c Well flow distribution during leakage from both injection wells.

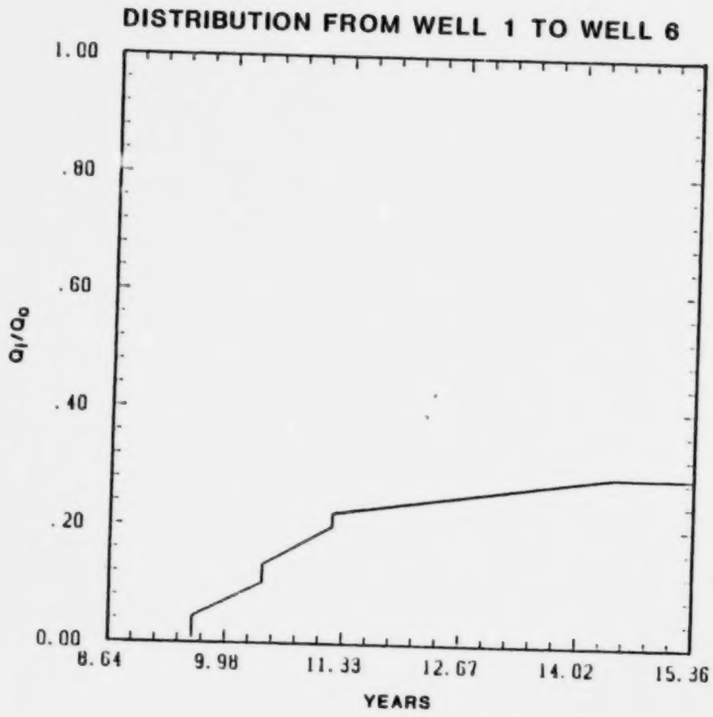


Figure 11.10d Well flow distribution during leakage from both injection wells.

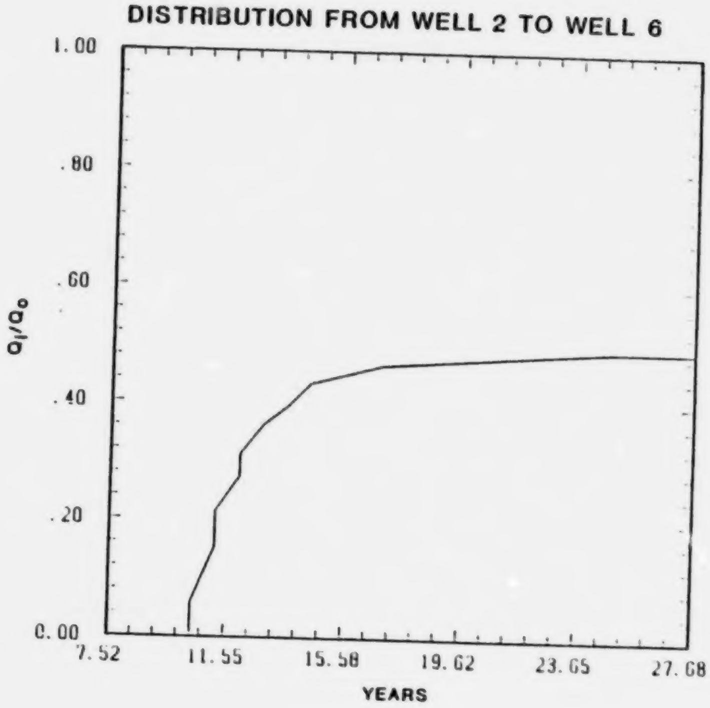


Figure 11.10e Well flow distribution during leakage from both injection wells.

Geochemical Modeling--

Water quality data from both geothermal (Appendix C) and nongeothermal (Table 11.1) Raft River KGRA waters data have been summarized and compared to use standards in Table 11.2. Some waters exceed standards for some of the parameters. For example, the fluoride standard is exceeded by all reported waters. Figure 11.11 is a Piper Diagram of geothermal and nongeothermal waters at Raft River. It can be seen that there is a continuum of waters from the geothermal wells through greater than 20°C irrigation wells to less than 20°C irrigation wells.

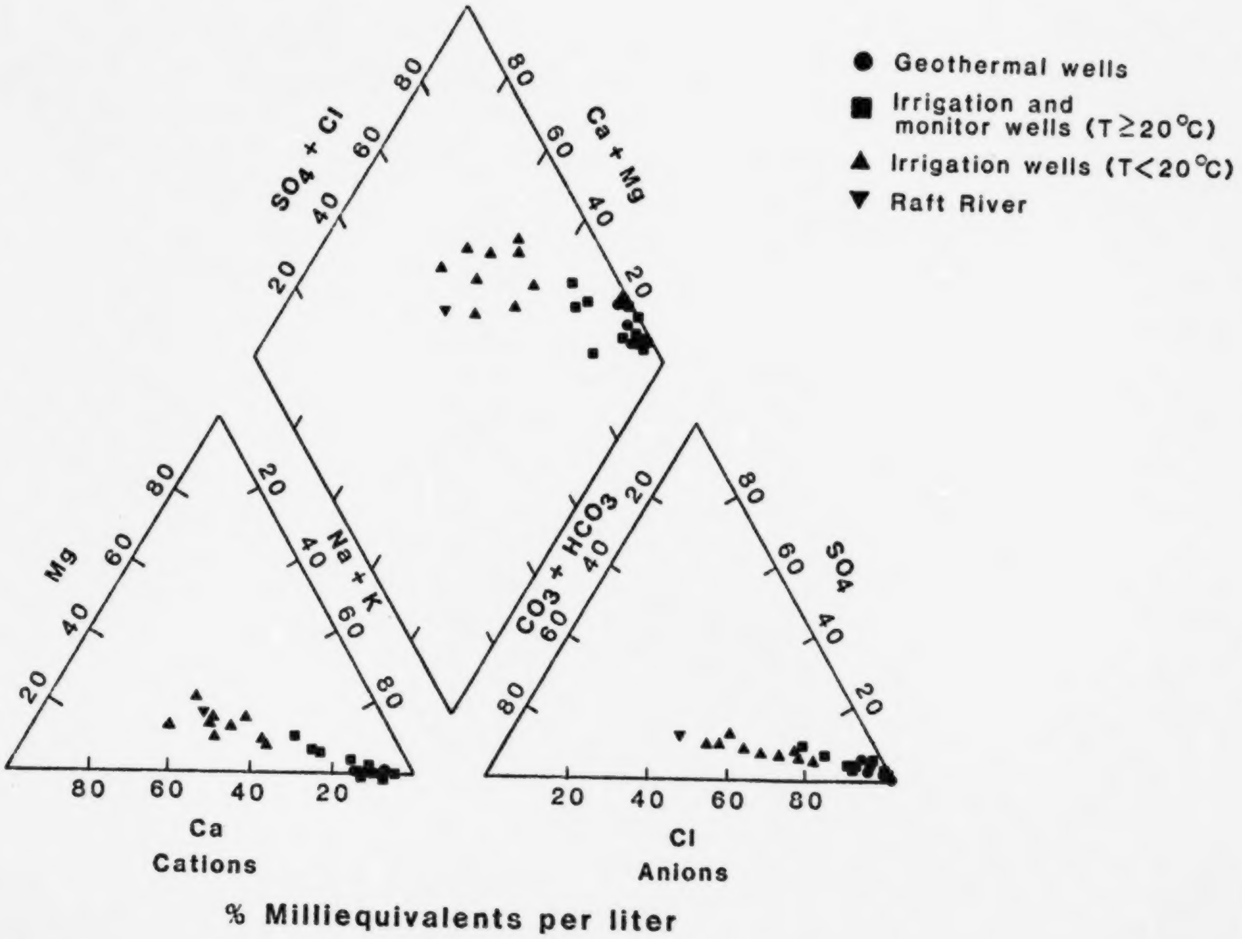
The above data indicate that the groundwaters are naturally impacted by the geothermal fluid. There is a mix of geothermal and nongeothermal waters making it difficult to detect small leaks.

Five groundwaters from the Raft River area were run through WATEQF to examine mineral-water equilibrium, two geothermal waters, two irrigation wells, and one injection well. Oxidation-reduction type reactions were not examined because of the lack of Eh data. The two geothermal waters were modeled at 30°C to investigate with respect to what minerals the geothermal water would be supersaturated. In general they are supersaturated with respect to silicate minerals, as are the nonthermal waters. The geothermal fluids are not expected to cause precipitation of minerals other than silicates.

Another way to examine the waters is to look for conservative ions. That is, ions that are associated with mineral phases that are undersaturated in both geothermal and nongeothermal waters. In the case of Raft River, F^- and SO_4^{-2} appear to be conserved. The ratio of SO_4^{-2}/F^- is higher in the nonthermal waters. Cation exchange reactions were not examined due to the lack of detailed aquifer mineralogical information. Another data insufficiency is the unknown chemistry of the injected fluids.

Select Monitoring Sites and Techniques

Exact monitoring sites cannot be located in a paper study such as this because of the lack of necessary field data. However, under Federal legislation, the following monitoring is required: 1) monitoring wells must be completed into the injection zone in which fluid levels and chemistry must be measured weekly, 2) monitoring well must be completed into overlying or nearby underground sources of drinking water in which quarterly measurements are to be made, 3) physical and chemical characteristics of the injection fluid must be measured with sufficient frequency to



gure 11.11 Piper Diagram of Waters from Raft River KGRA (modified from Spencer and Callan, 1980)

TABLE 11.2 CHEMICAL PARAMETERS OF CONCERN, RAFT RIVER KGRA

Constituent	Geothermal Fluid Range mg/l	Geothermal Fluid Violations*	Nongeothermal Waters Range mg/l	Nongeothermal Waters Violations*
Eh				
pH	6.8-7.6		7.1-7.8	
TDS	1318-6227	D,I,	720-6270	D,I
Al	minor trace			
As	<.05			
B	.2-.25			
Ba	<.4			
Ca	35-280	D	107-230	D
Cd				
Cl	614-3640	D	197-3680	D
Cr				
Cu				
F	4.4-9.0	D,I,L	.4-5.4	D,I,L
Fe	.32-.8			
HCO_3	41-73		41-182	
Hg				
K	27-105		5.9-56	
Li	1.1-5.1	I	.1-3.7	I
Mg	.13-2.7		.4-27	
Mn	.06-.2	D,L		
Na	389-2100	D	71-2220	D
NH_4	.15-1.99	D		
Ni	3.6-3.7	D,I		
Pb	trace			
Sb				
Se				
SiO_2	94-170		46-87	
SO_4	32-67		27-90	
Sr	.9-10			
Zn				

*D=Drinking Water Standards
I=Irrigation Water Standards
L=Livestock Water Standards

yield representative data, 4) injection pressure, flow rate, and volume must be continuously monitored, and 5) the results must be reported quarterly to the Director of the UIC program.

Results of the contaminant transport simulation indicate that a pollutant plume would move slowly to the north in the unconfined surface aquifer. Travel times to the nearest municipal and agricultural wells would be on the order of 200 years. Thus monitoring wells completed into the shallow groundwater should in general be located north of production and injection wells. Monitoring wells completed into the injection zone should be located between the injection and production wells.

Gross chemical and selected trace element analyses should be performed on water samples from the wells. The set of trace elements cannot be recommended here due to the lack of complete chemical data. The data does indicate that F^- and Li^+ may be useful trace elements. The SO_4^{2-}/F^- ratio may also be a good indicator. Since the groundwater has been naturally impacted by the geothermal fluid, it will be difficult to detect leaks from the wells using monitoring wells. Measurements on the production and injection wells will be the key to detecting leaks. Changes in pressures, flow rates, temperatures and fluid chemistries might indicate a problem with the wells. Monitoring wells will act both to detect leaks as a backup to monitoring the production and injection wells themselves and as an assessment tool for determination of the impact of a leak on the groundwater system.

GROUNDWATER CONTAMINATION FROM A LAGOON

Geothermal fluids stored in a holding pond or lagoon could be a source of groundwater contamination. These fluids tend to percolate out of the holding area and into the groundwater where they may be transported and mixed with the ambient flow. POLLUTE was used to devise a scheme where all the contaminated groundwater would be intercepted by one or more pumping wells and be removed from the aquifer.

The lagoon, bounded in the south by a fault, was monitored for leachate by four observation wells to the east (Figure 11.12). The ambient groundwater flow was from west to east with a gradient of 0.001. Aquifer characteristics included a hydraulic conductivity of 200 ft/day, and a porosity of 0.2. The fault in the south also bounded the aquifer and was considered an impermeable boundary. Contaminants leached into the groundwater below the lagoon at a rate of 3273 cubic feet per day.

POLLUTE simulated the rectangular lagoon by dividing it into two distinct injection wells with radii of 600 feet (Figure 11.13). Flow paths emanating from the periphery of the injection

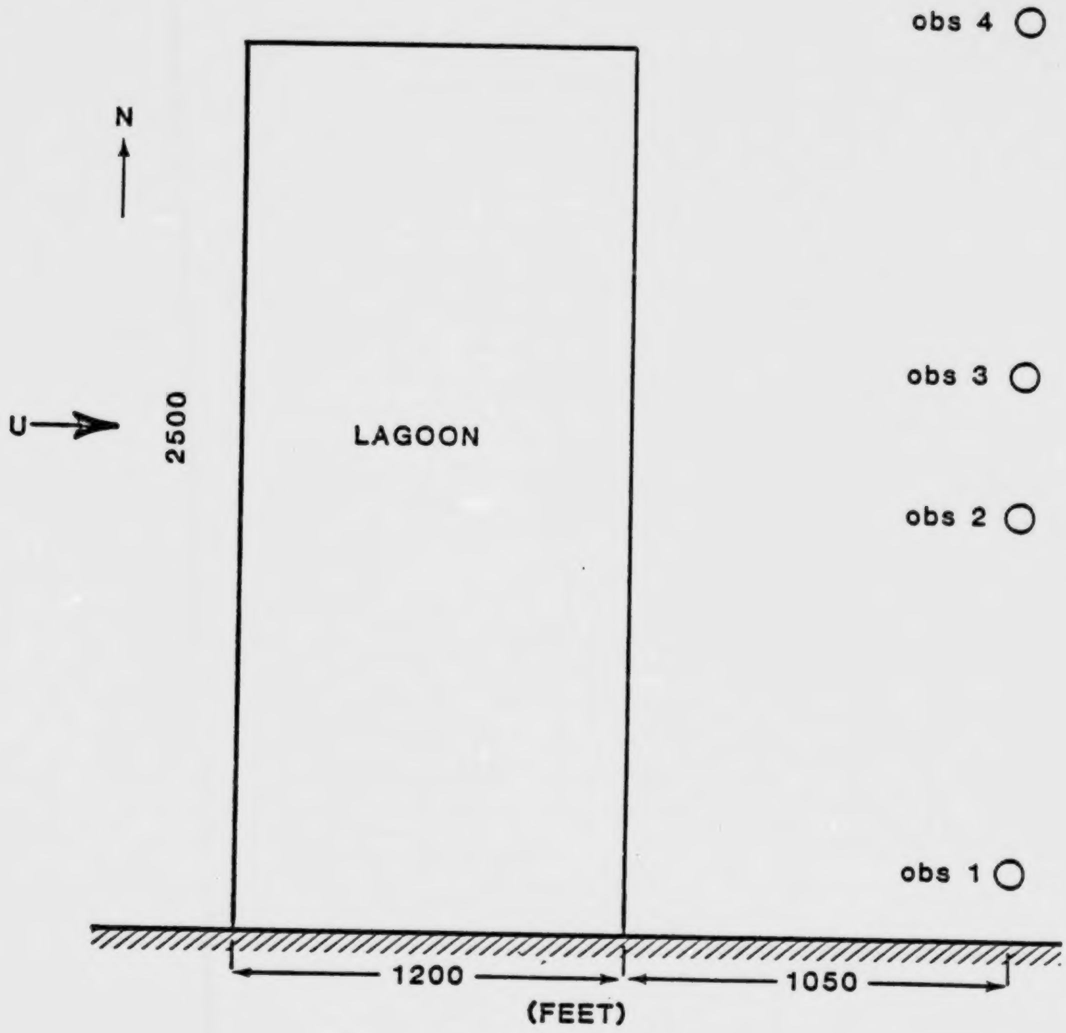

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Figure 11.12 Map view of lagoon and observation wells.

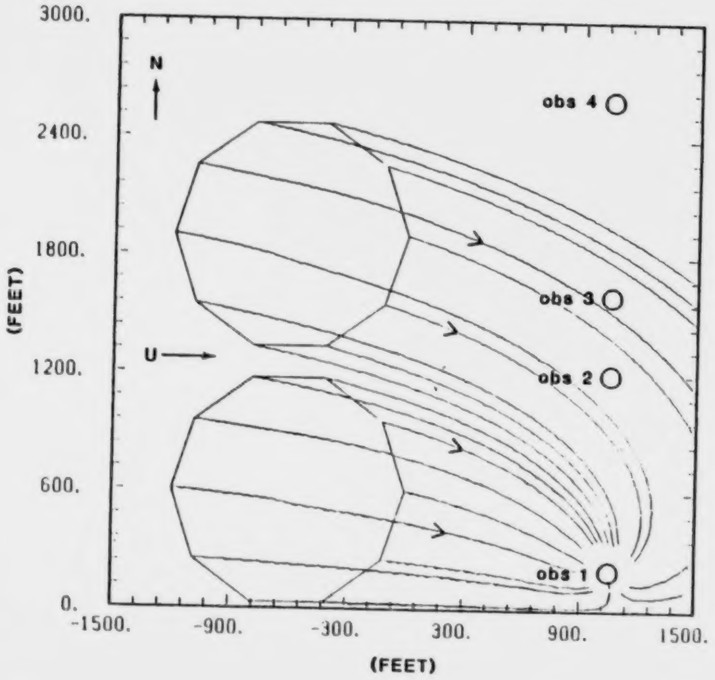


Figure 11.13 Interception of lagoon leachate by single pumping well. Pumping rate is 0.8 cfs.

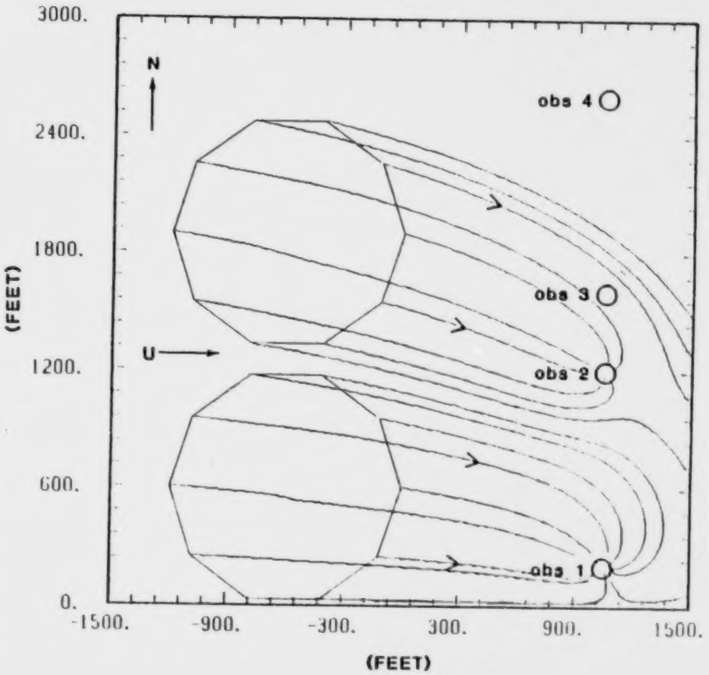


Figure 11.14 Interception of lagoon leachate by dual pumping wells. Total pumping rate is 0.8 cfs.

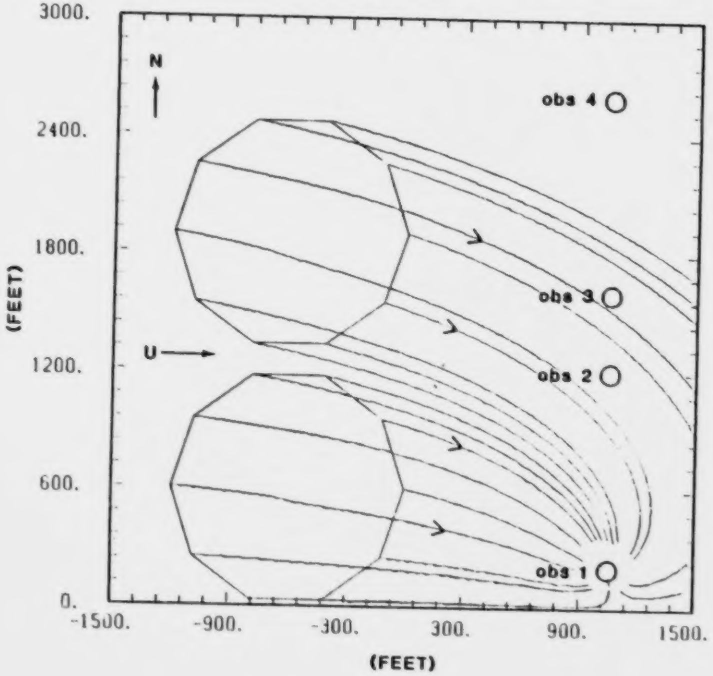


Figure 11.13 Interception of lagoon leachate by single pumping well. Pumping rate is 0.8 cfs.

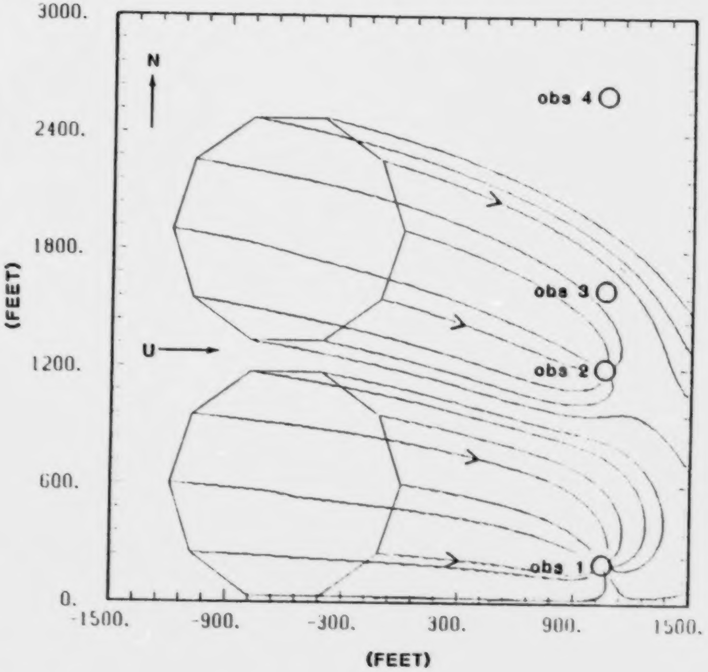


Figure 11.14 Interception of lagoon leachate by dual pumping wells. Total pumping rate is 0.8 cfs.

wells were calculated until they were either intercepted at the pumping well(s) or had exceeded 500 iterations (which would occur outside the study area). Since the recharge of each injection well was not sufficient to displace the local ambient groundwater, many flow lines passed through the injection wells instead of circumventing them. Had the lagoon not been above the water table, a component for flow into a cylinder would have been required in the main algorithm due to the large radii of the injection wells.

The first scenario attempted with POLLUTE utilized observation well 1 as the sole pumping well with a discharge rate of 0.8 cubic feet per second (cfs). As shown in Figure 11.13, all but three flow lines were intercepted by the pumping well.

In the second scenario, the previous pumping rate (0.8 cfs) was divided between observation wells 1 and 2 in an attempt to intercept all lagoon contaminated groundwater flow (Figure 11.14). However, three of the twenty flow lines emanating from the lagoon still escaped into the ambient aquifer system indicating that the 0.8 cfs discharge rate was 80-85 percent of the necessary pumping rate.

The third and fourth scenarios used the previous single and double pumping well configurations discharging a total of 1 cfs. Figures 11.15 and 11.16 show that the 1 cfs discharge rate was sufficient in both scenarios to intercept all contaminants leaching from the lagoon.

In all four scenarios, the observation wells closest to the impermeable boundary were used as pumping wells since they were least likely to intercept noncontaminated ambient groundwater from beyond the lagoon (to the north). Had observation well 3 or 4 been used at the 1 cfs rate, interception of the noncontaminated ambient groundwater north of the lagoon would have occurred resulting in some contaminated groundwater escaping beyond the well.

CONTAMINANT PLUME TRACKING AND INTERCEPTION

The next example is a hypothetical example of the use of POLLUTE to delineate and rectify a specific groundwater pollution problem. Most of the graphical output given by POLLUTE is utilized in solving the pollution problem, emphasizing interrelationships between the various types of output.

Two small municipalities, which rely upon groundwater for their water supplies are located just west of a large lake (Figure 11.17). Further to the west lies the XYZ Chemical Company which disposed of chemical wastes through subsurface

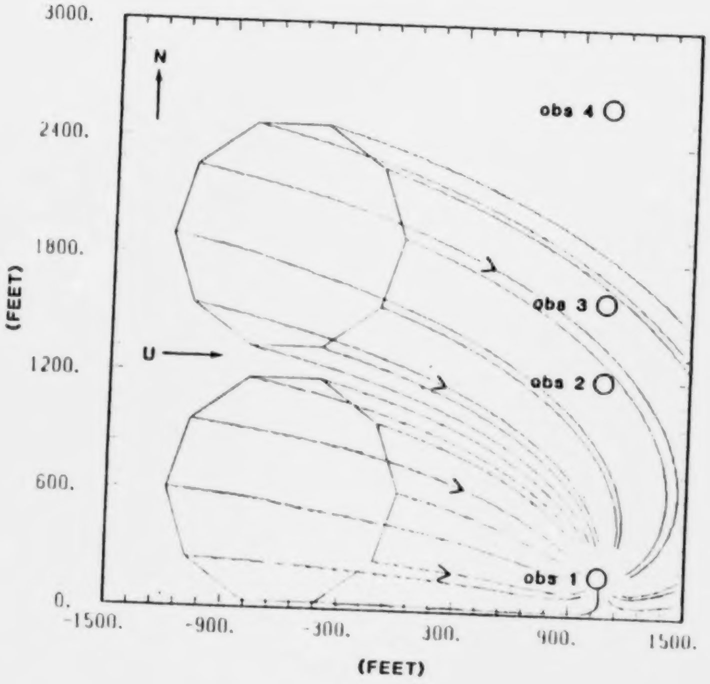


Figure 11.15 Interception of lagoon leachate by single pumping well. Pumping rate is 1.0 cfs.

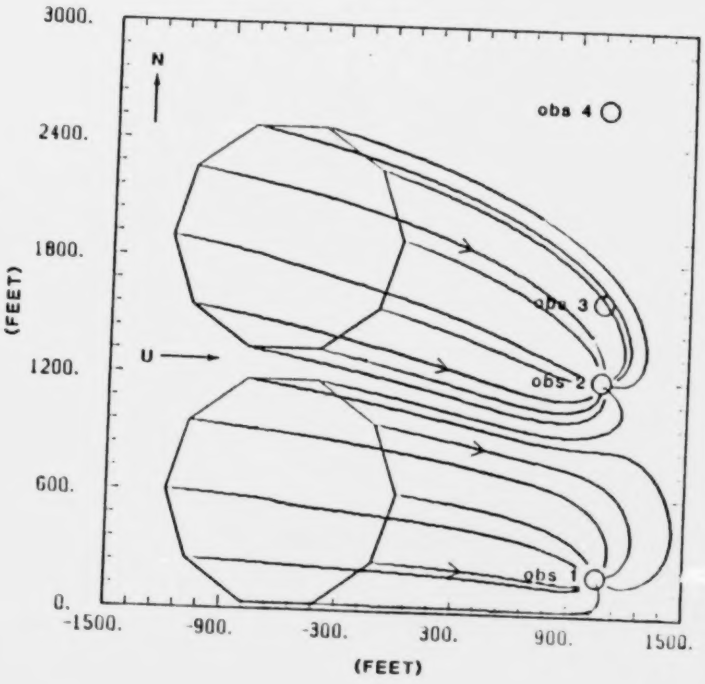
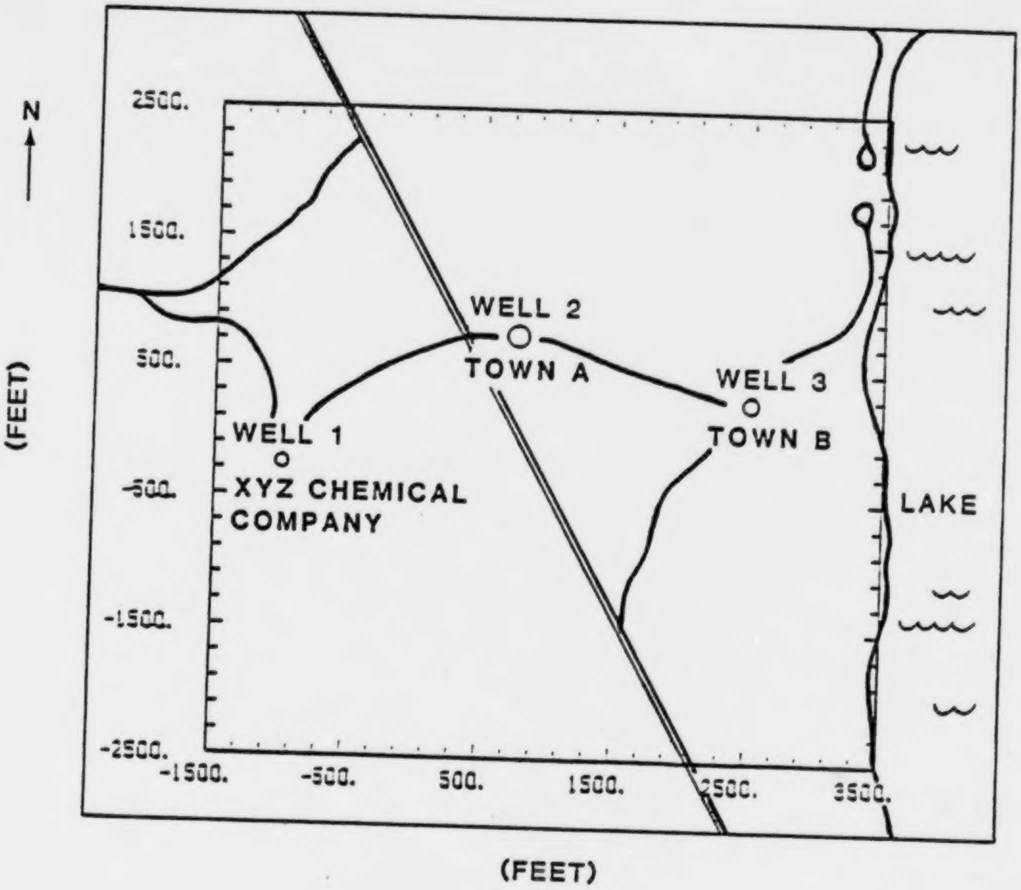


Figure 11.16 Interception of lagoon leachate by dual pumping wells. Total pumping rate is 1.0 cfs.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WELL 2
TOWN A
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TOWN B
WELL 1
XYZ CHEMICAL
COMPANY
LAKE

Figure 11.17 Map view of study area.

injection. Underlying the entire study area and terminating at the lake is a confined sandstone aquifer. The aquifer has a uniform ambient flow gradient from the west of 0.002, a porosity of 0.2, a hydraulic conductivity of 27.4 feet per day, and a uniform saturated thickness of 100 feet. Town A is pumping at a rate of 0.32 cfs out of the sandstone aquifer and Town B is pumping at a rate of 0.48 cfs out of the same aquifer.

In 1971, the XYZ Chemical Company started injecting wastes into the sandstone aquifer at a rate of 0.16 cfs. Figure 11.18 shows the groundwater regime in the study area from the pumping and injection activities of the two towns and the chemical company. Figure 11.19 indicates that Town A should start intercepting chemical wastes approximately eight years after the XYZ Chemical Company started injecting them into the aquifer. In 1979, Town A discovered contaminants in its water supply and immediately shut down its well. The contaminants were traced back to the XYZ Chemical Company which immediately closed down its well also. From the isochron map given by POLLUTE (Figure 11.20) previous to the well shutdowns, the extent of the eight-year-old contaminant plume was delineated (Figures 11.20 and 11.21).

After the shutdown of Town A and XYZ Chemical Company wells, the contaminant plume was still present in the groundwater. The groundwater flow regime had been altered by the well shutdowns to where the contaminant plume would ultimately contaminate Town B's water supply (Figure 11.22). Another pumping well was needed between Town B and the contaminant plume to intercept the plume before reaching the town. Such a well pumping at a rate of 0.24 cfs was introduced as shown in Figure 11.23. The 0.24 cfs pumping rate was slightly larger than was apparently needed, which enabled the pumping well to intercept contaminants that may have dispersed and/or diffused beyond the calculated plume boundary.

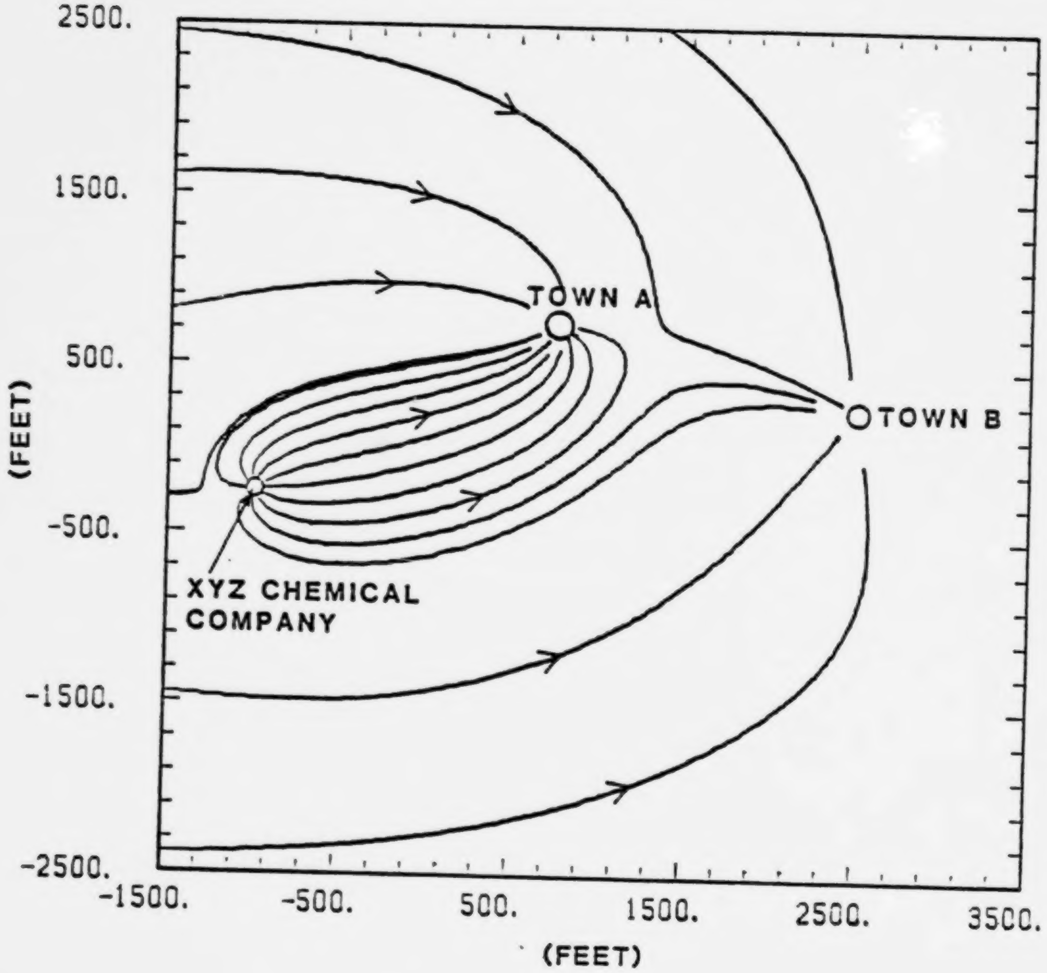


Figure 11.18 Groundwater flow regime during pumping by Town A and Town B, and injection by the XYZ Chemical Company.

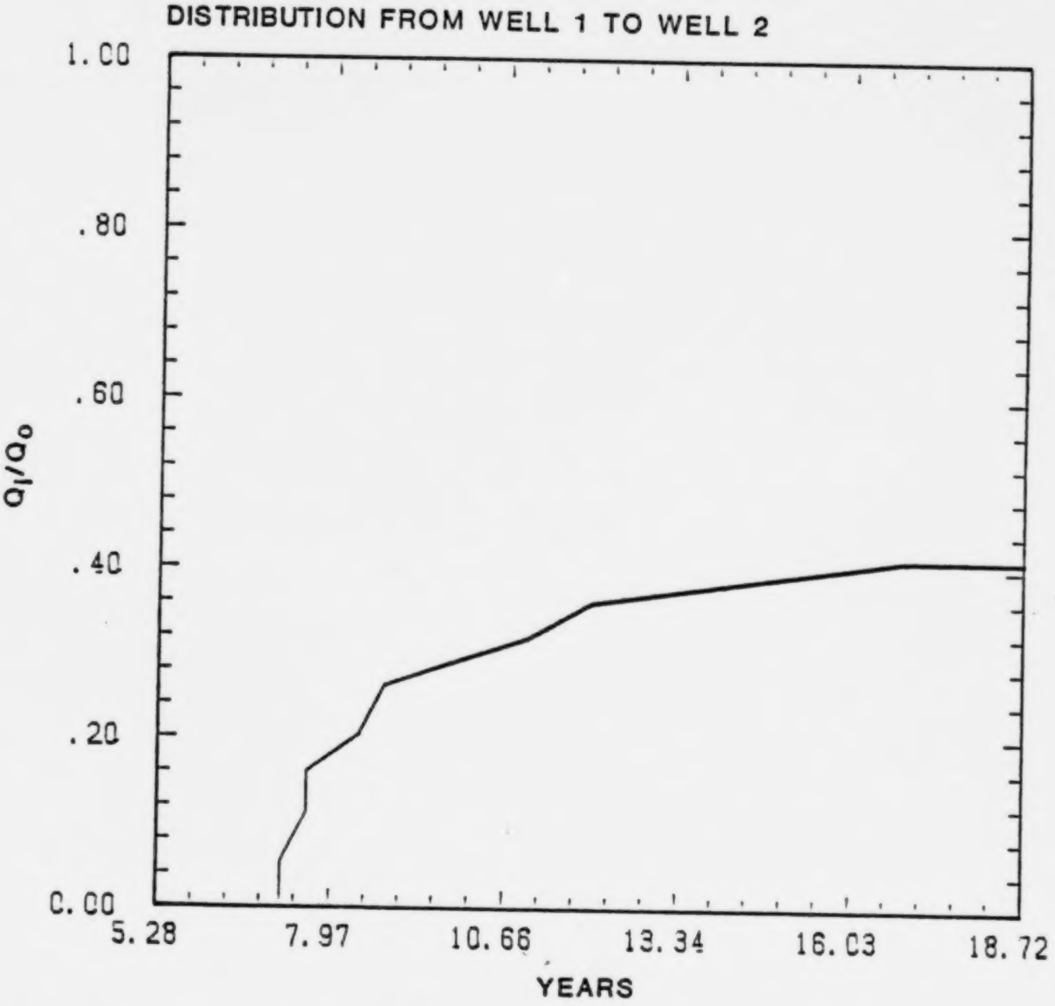
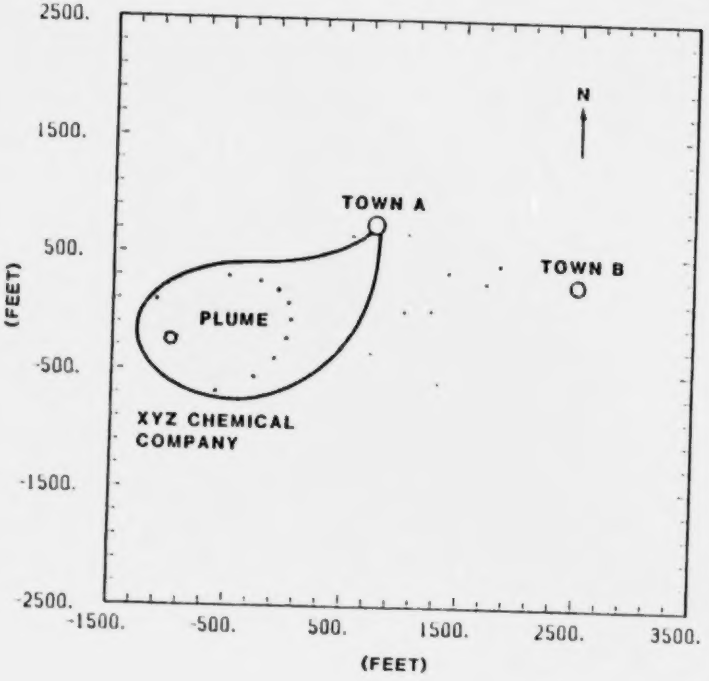


Figure 11.19 Well flow distribution at Town A from the XYZ Chemical Company.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XYZ CHEMICAL
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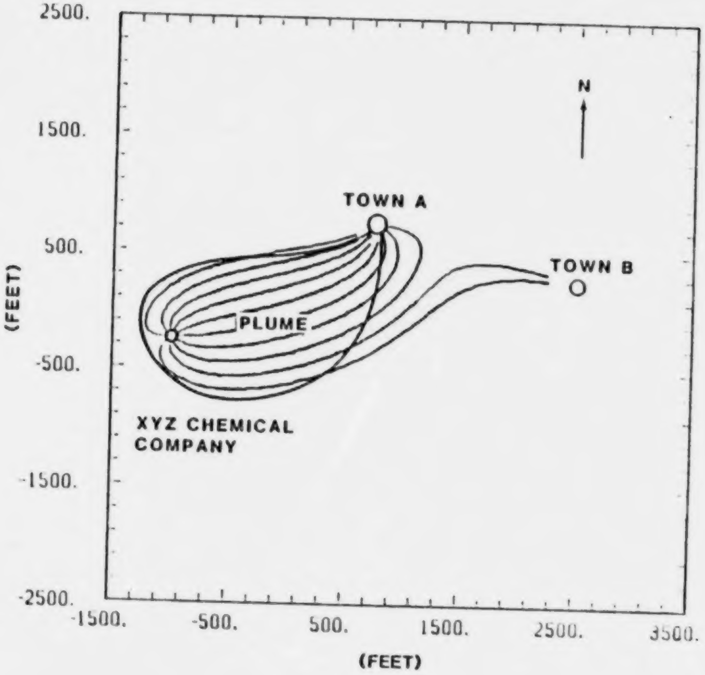
Figure 11.20 Outline of contaminant plume on isochron map after 8.0 years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(FEET)
N
TOWN A
TOWN B
PLUME
XYZ CHEMICAL
COMPANY

Figure 11.21 Outline of contaminant plume on flow regime just prior to well shutdowns by Town A and the XYZ Chemical Company

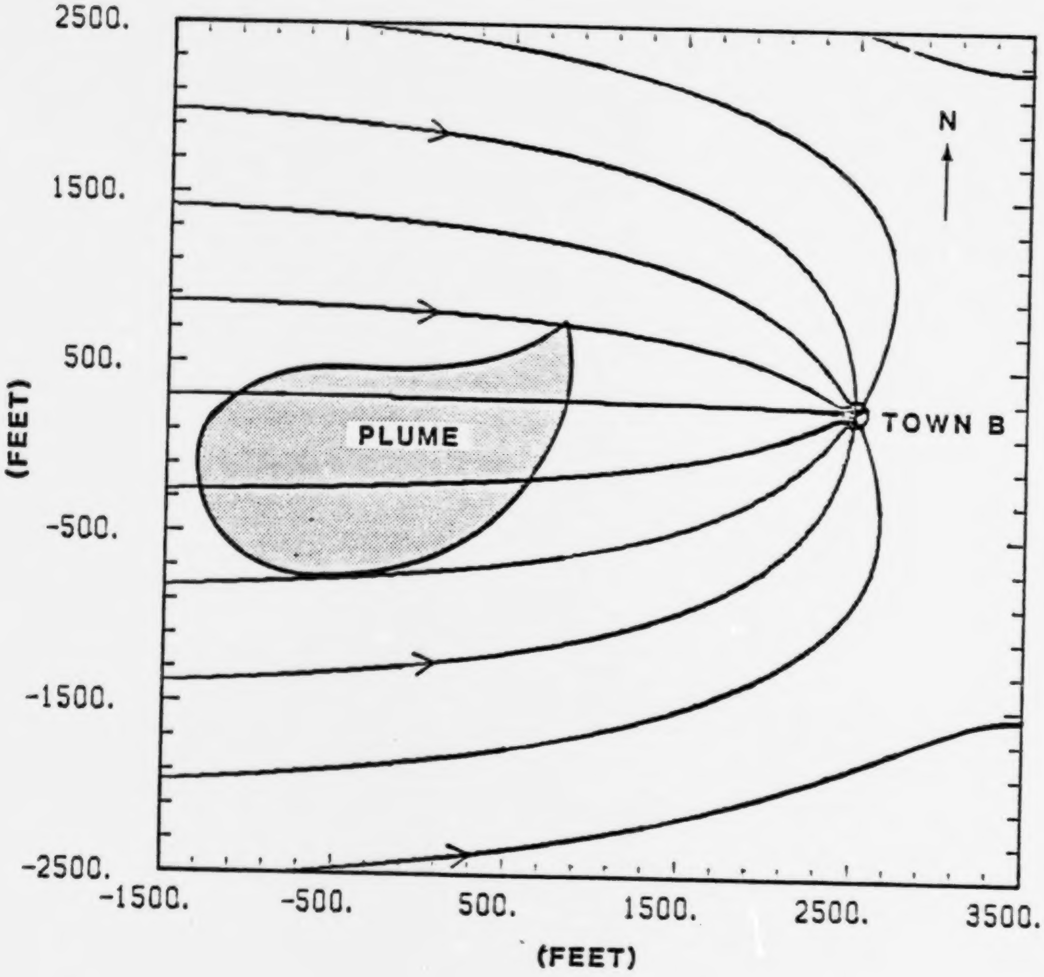

Figure 11.22 Outline of contaminant plume on flow regime with only Town B pumping.

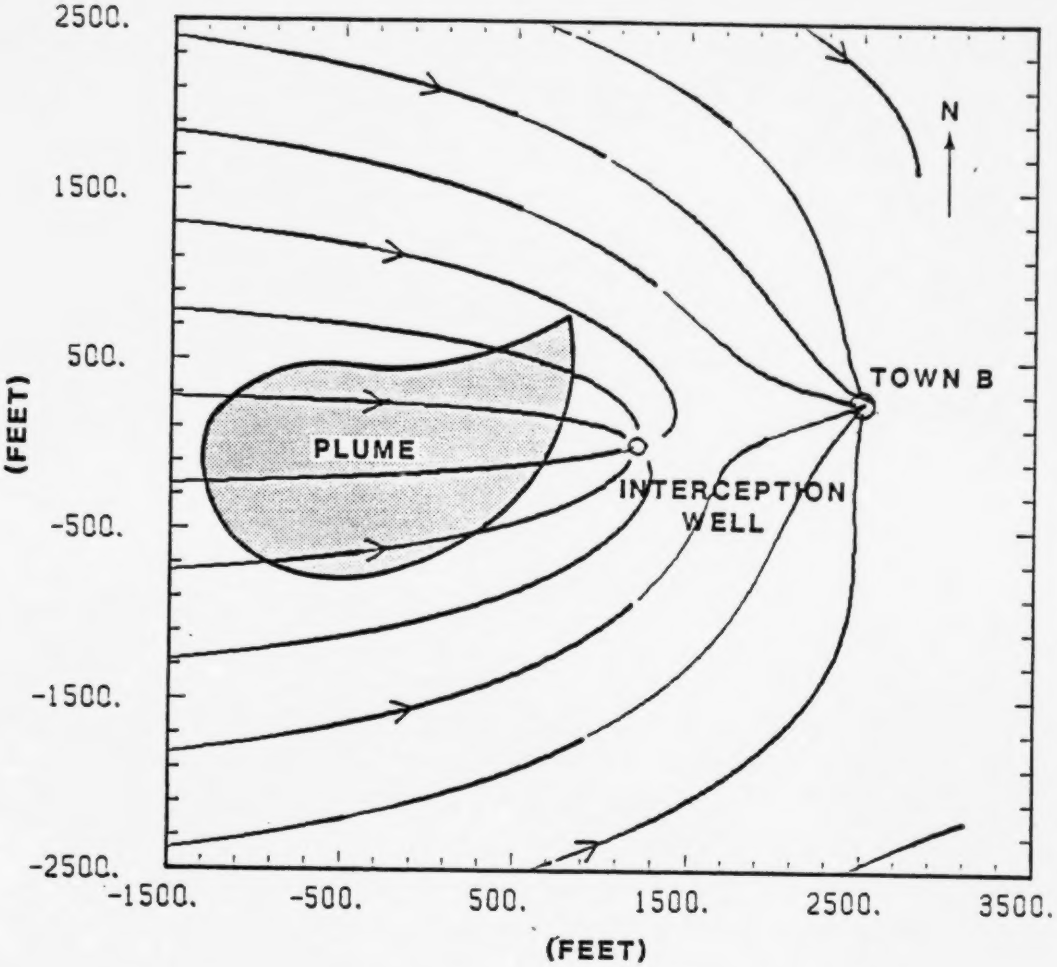
2500.
1500.
500.
-500.
-1500.
-2500.
-1500.
-500.
500.
1500.
2500.
3500.
(FEET)
(FEET)
N
PLUME
INTERCEPTION WELL
TOWN B

Figure 11.23 Interception well emplaced to intercept contaminant plume.

REFERENCES

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4. Mundorff, M. and H. Sisco, 1963, Ground Water in the Raft River Basin, Idaho with Special Reference to Irrigation Use, 1956-60, USGS Water-Supply Paper 1619-CC, 23 p.

5. Nace, R., et al, 1961, Water Resources of the Raft River Basin, Idaho-Utah, USGS Water Supply Paper 1587, 138 p.

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8. Spencer, S. and D. Callan, 1980, An Analysis of the Response of the Raft River Monitor Wells to the 1979 Injection Tests, EGG-2057, 27 p.

9. Walker, E., L. Dutcher, S. Decker and K. Dyer, 1970, The Raft River Basin, Idaho-Utah, as of 1966: A reappraisal of the Water Resources and Effects of Ground-water Development, Idaho Dept. of Water Admin. Info. Bull. 19.

APPENDIX A

POLLUTE User's Guide

Although the input data is described within the program itself, more detail is needed on the utility and function of several of the input parameters for program usability.

Data card 2 defines the location of a rectangular study area and also the number of ambient flow lines to be plotted. This differs with data card 11 which locates a rectangular plotting window within the study area.

If any ambient flow lines are to be plotted, it is important to locate point (0,0) within the study area since the origin of the ambinet flow lines are located upgradient from that point. The ambient flow lines origins are evenly distributed along a linear segment which is perpendicular to the uniform flow gradient. The distance from the origin to the center of this linear segment is equal to the diagonal of the study area rectangle, which ensures that the ambient flow line origins are beyond the study area. The length of the linear segment is determined by the uniform flow distribution parameter (UFDIST) of card 6. With a UFDIST equal to 1.0, the segment length is equal to the length of the y axis boundary of the study area. Doubling UFDIST doubles the segment length, and so on.

The well radius parameter of input cards 4 do not necessarily reflect the actual well radius, but may be an exaggerated radius. Exaggeration of the well radius may be desired for plotted output clarity and as a method to prevent numerical error. An exaggerated well radius of 50 to 100 feet is recommended (depending upon scale of plotting window).

As per input card 4, if the well discharge is unknown, the well drawdown/drawup may be used and POLLUTE will calculate a discharge. However, in calculating the discharge, POLLUTE assumes that no other source/sink affects the head in the well other than the source/sink at the well itself. This assumption may cause the well discharge to be in error if other sources and/or sinks are in close proximity. This same assumption may also cause error in the Local Head column of the printed output (see input/output example below).

The middle parameter of input card 6 defines the time increment used in the calculations of the flow lines. If it is set equal to zero, POLLUTE will define its own time increment. This is done by determining what time increment would be sufficient to traverse a flow line along the x axis across the plotting window in 250 iterations assuming a uniform glow gradient at 270° and no source or sinks.

Illustration of the data prompters and printed output produced by POLLUTE can be seen in the following example. Data was entered from a separate data as a response to each prompter. Plotted output from this data set resulted in Figures 8.6, 8.7, 8.8, 8.10a, and 8.13a as well as an isochron plot (not presented).

The printed output includes initial location, termination location, number of iterations, and travel time for each flow line. POLLUTE calculates flow lines as they emanate from their respective injection well and numbers them consecutively in a counterclockwise fashion starting with the first flow line north (north is up) of the easternmost point on the well radius (which is the location of the final flow line for that well).

The cumulative flow from each flow path, also included in the printed output, range from zero to one and is the cumulative percentage of flow that each flow line represents. Any out-of-sequence-values indicate possible error in the well flow distribution plots.

Following the input/output example are the listings for SOLUTE and POLLUTE that were used in the comparisons. Results of these data sets are shown in Figures 8.21, 8.22, 8.23, 8.24, and Table 8.1.

A flow chart schematically depicting the sequence of operations within POLLUTE immediately follows the SOLUTE/POLLUTE data sets. The function of the flow chart is to assist the user in locating unforeseen program errors that may occur during future use. The flow chart may also serve as a structure guide for subsequent modifications. In the interest of clarity, only those subroutines with the most important functions are shown.

```
******************** INPUT/OUTPUT EXAMPLE **********************


 ENTER; DATA SET # START, DATA SET # END
      FOR ONLY ONE DATA SET, ENTER; 1,1
 DATA SET    1

 ENTER FOR ENTIRE STUDY AREA;
X MIN, X MAX, Y MIN, Y MAX, NUM UNIF FLOW LINES (INT)
 INPUT THE TOTAL NUMBER OF WELLS(01 TO 20)
  AND TOTAL NUMBER OF WELL-FLOW LINES (01 TO 80)
 WELL- 1

 ENTER: XCOORD, YCOORD, WELL RADIUS, DISCHARGE, HEAD
           L       L           L        (L**3)/T    L

 IF DISCHARGE IS KNOWN, SET HEAD = 0.0
 WELL- 2

 ENTER: XCOORD, YCOORD, WELL RADIUS, DISCHARGE, HEAD
           L       L           L        (L**3)/T    L

 IF DISCHARGE IS KNOWN, SET HEAD = 0.0
 ENTER: AVG DEPTH, POROSITY, UNIF GRAD, HYDR K, AVG RADIUS OF INFLUENCE
            L                   L/L     L/T                       L
 ENTER; ANGLE OF UNIFORM FLOW (DEGREES)
 N= 0.0, E= 90., W= 270., S= 180.
 ENTER; OPTIONAL TIME INCREMENT (0.0 = AUTOMATIC)
 ENTER; UNIF FLOW DIST SIZE, 3.0=SUGESTED

 ENTER: ANISOTROPY ALONG   X-AXIS,YAXIS
 EXAMPLES: IF ISOTROPIC ENTER   1.,1.
           IF ANISOTROPIC ALONG X-AXIS BY A FACTOR OF THREE,
              ENTER   3.,1.
 ENTER NUMBER OF BOUNDARIES (ZERO=0)
 ENTER: MIN X, MAX X, MIN Y, MAX Y (FOR WINDOW)
 AND NPLOT CODE


1

WELL       XCOORD       YCOORD       RADIUS    LOCAL HEAD      DISCHARGE

  1         -250.        250.         40.0       18.46      15000000.00
  2          500.        125.         40.0      -18.46     -15000000.00

THERE ARE   2 PUMPING AND/OR RECHARGING WELLS
```

```
******************** INPUT/OUTPUT EXAMPLE **********************



WELL RECHARGE =      15000000.00            8 FLOW PATHS

INITIAL LOCATION IS (    -221.72,    278.28)                34 ITERATIONS
PATH  1 OF WELL  1 ARRIVED AT WELL  2 IN      .51 YEARS

INITIAL LOCATION IS (    -250.00,    290.00)                55 ITERATIONS
PATH  2 OF WELL  1 ARRIVED AT WELL  2 IN      .83 YEARS

INITIAL LOCATION IS (    -278.28,    278.28)               500 ITERATIONS
PATH  3 OF WELL  1 ARRIVED AT ( 2726.45,    98.21)  IN   7.68 YEARS

INITIAL LOCATION IS (    -290.00,    250.00)               145 ITERATIONS
PATH  4 OF WELL  1 ARRIVED AT WELL  2 IN     2.21 YEARS

INITIAL LOCATION IS (    -278.28,    221.72)                57 ITERATIONS
PATH  5 OF WELL  1 ARRIVED AT WELL  2 IN      .86 YEARS

INITIAL LOCATION IS (    -250.00,    210.00)                35 ITERATIONS
PATH  6 OF WELL  1 ARRIVED AT WELL  2 IN      .52 YEARS

INITIAL LOCATION IS (    -221.72,    221.72)                27 ITERATIONS
PATH  7 OF WELL  1 ARRIVED AT WELL  2 IN      .40 YEARS

INITIAL LOCATION IS (    -210.00,    250.00)                27 ITERATIONS
PATH  8 OF WELL  1 ARRIVED AT WELL  2 IN      .40 YEARS


THE CUM FLOW FOR PATH   1 IS;     .12981
THE CUM FLOW FOR PATH   2 IS;     .26165
THE CUM FLOW FOR PATH   3 IS;     .37745
THE CUM FLOW FOR PATH   4 IS;     .48275
THE CUM FLOW FOR PATH   5 IS;     .58872
THE CUM FLOW FOR PATH   6 IS;     .70631
THE CUM FLOW FOR PATH   7 IS;     .84024
THE CUM FLOW FOR PATH   8 IS;     .98551


          .015 YEARS, IS THE TIME INCREMENT

ISOCHRONE PLOTTED EVERY      .31 YEARS
```

```
******************** INPUT/OUTPUT EXAMPLE ***********************


 POLYNOMIAL WELL FLOW DISTRIBUTION FROM WELL   1 TO WELL   2

Y = A + (B1)(X**1) + (B2)(X**2) +...+ (BN)(XN**)

WHERE   A  =        -1.4779
        B1 =         6.2568
        B2 =        -6.2314
        B3 =         2.6503
        B4 =         -.4031

WITH A STND DEV OF S =           .0627
```

```
***************** DATA SET FOR INPUT/OUTPUT EXAMPLE ******************


1,1
-1000.,1000.,-1000.,1000.,0
2,8
-250.,250.,40.,15000000.,0.
500.,125.,40.,-15000000.,0.
70.,.2,.0095,10950.,15000.
270.,0.,3.
1.,1.
0
-1000.,1000.,-1000.,1000.,4
```

********** DATA SET FOR NUMERICAL COMPARISON - SOLUTE **********

```
NUMERICAL COMPARISON BETWEEN SOLUTE AND POLLUTE
NONDISPERSIVE
   1   1  16  183200    1    7    0 100    2    9    1   10    1    0    1    0
  5.0.0001 0.20  0.0   0.0   0.0   0.0 200. 200.  0.0 0.50  1.0
 5 7 -.4756  0.0
 712  .4756
0 .0347
0 100.
0 0.0
1 1.0
0000000000000000
0111111111111110
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0111111111111110
0000000000000000
 1  1.0        0.0       0.0      0
1  1.0

0.00115.115.115.115.115.115.115.115.115.115.115.115.115.115.0.00






0.0 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 0.0
```

```
********** DATA SET FOR NUMERICAL COMPARISON - SOLUTE ***********


0  0.0
```

*********** DATA SET FOR NUMERICAL COMPARISON - SOLUTE ************

```
NUMERICAL COMPARISON BETWEEN SOLUTE AND POLLUTE
DISPERSIVE
    1    1   16   183200    1    7    0 100    2    9    1   10    1    0    1    0
  5.0.0001 0.20 100.  0.0  0.0  0.0 200. 200.  .33 0.50  1.0
 5 7 -.4756  0.0
 712   .4756
0 .0347
0 100.
0 0.0
1 1.0
0000000000000000
0111111111111110
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0000000000000000
0111111111111110
0000000000000000
  1  1.0        0.0       0.0      0
1  1.0

0.00115.115.115.115.115.115.115.115.115.115.115.115.115.115.0.00
```

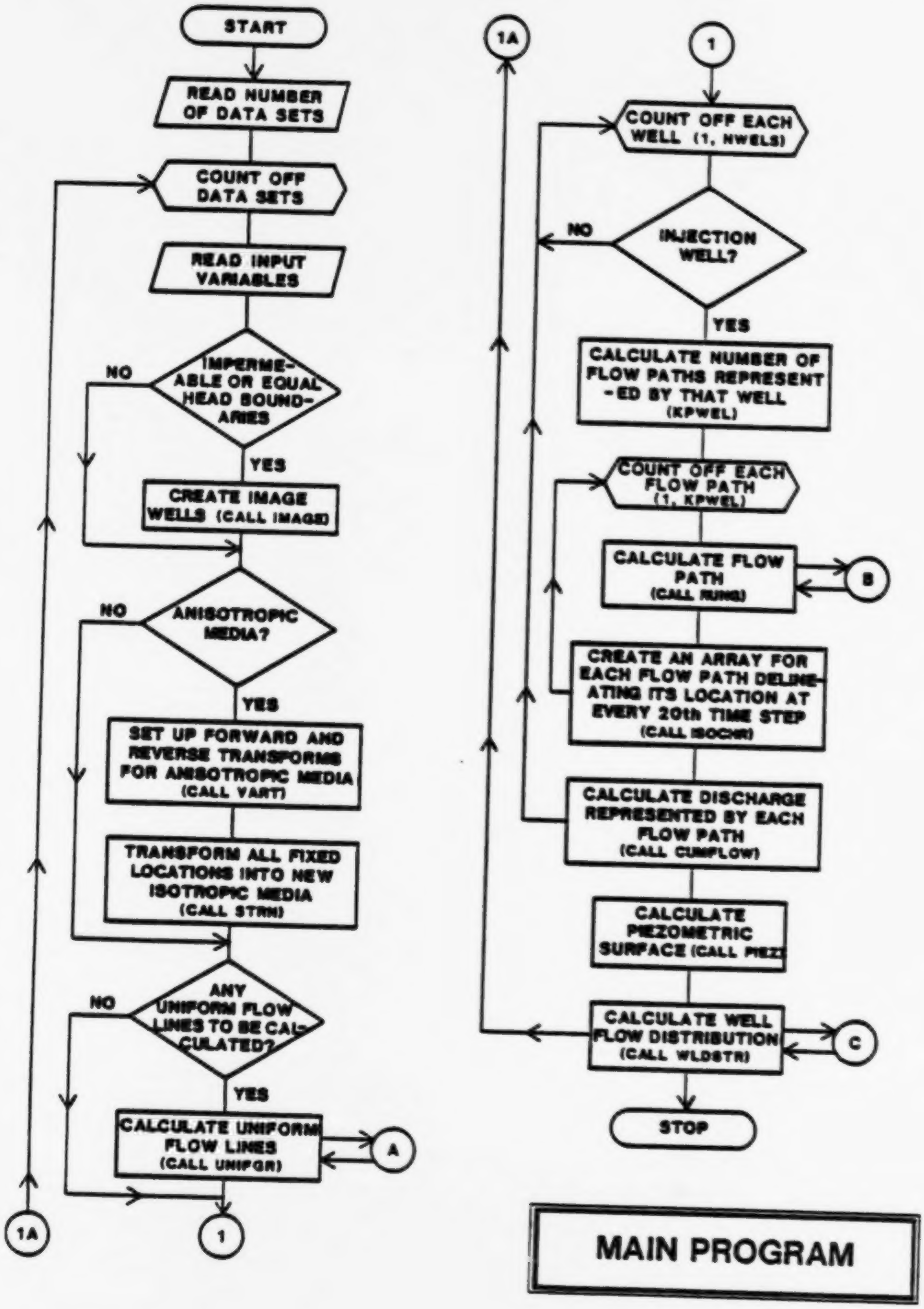
```
0.0 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 0.0
```

```
*********** DATA SET FOR NUMERICAL COMPARISON - SOLUTE ***********


0  0.0
```

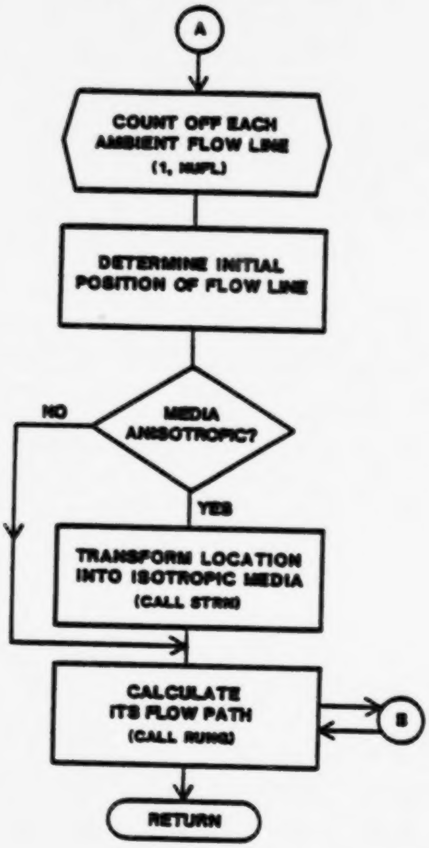
```
********** DATA SET FOR NUMERICAL COMPARISON - POLLUTE ***********


 1  1
 1
 -1600.,1600.,-1600.,1600.,0
 2,25
 -700.,500.,50.,15000000.,0.
 -300.,-500.,50.,-15000000.,0.
 100.,.2,.005,10950.,15000.
 0.,0.,3.
 0,0
 4
 -100000000.,140000000000.,1
 100000000.,140000000000.,1
 .0000000001,1400.,-1
 .0000000001,-1400.,-1
-1600.,1600.,-1600.,1600.,4
```

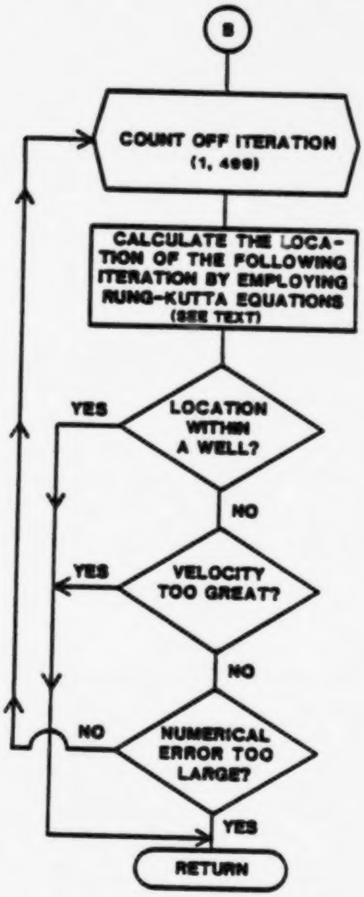

START
READ NUMBER OF DATA SETS
COUNT OFF DATA SETS
READ INPUT VARIABLES
IMPERMEABLE OR EQUAL HEAD BOUNDARIES
NO
YES
CREATE IMAGE WELLS (CALL IMAGE)
ANISOTROPIC MEDIA?
NO
YES
SET UP FORWARD AND REVERSE TRANSFORMS FOR ANISOTROPIC MEDIA (CALL VART)
TRANSFORM ALL FIXED LOCATIONS INTO NEW ISOTROPIC MEDIA (CALL STRN)
ANY UNIFORM FLOW LINES TO BE CALCULATED?
NO
YES
CALCULATE UNIFORM FLOW LINES (CALL UNIFGR)
A
1A
1
1A
1
COUNT OFF EACH WELL (1, NWELS)
INJECTION WELL?
NO
YES
CALCULATE NUMBER OF FLOW PATHS REPRESENTED BY THAT WELL (KPWEL)
COUNT OFF EACH FLOW PATH (1, KPWEL)
CALCULATE FLOW PATH (CALL RUNG)
B
CREATE AN ARRAY FOR EACH FLOW PATH DELINEATING ITS LOCATION AT EVERY 20th TIME STEP (CALL ISOCHR)
CALCULATE DISCHARGE REPRESENTED BY EACH FLOW PATH (CALL CUMFLOW)
CALCULATE PIEZOMETRIC SURFACE (CALL PIEZ
CALCULATE WELL FLOW DISTRIBUTION (CALL WLDSTR)
C
STOP

MAIN PROGRAM

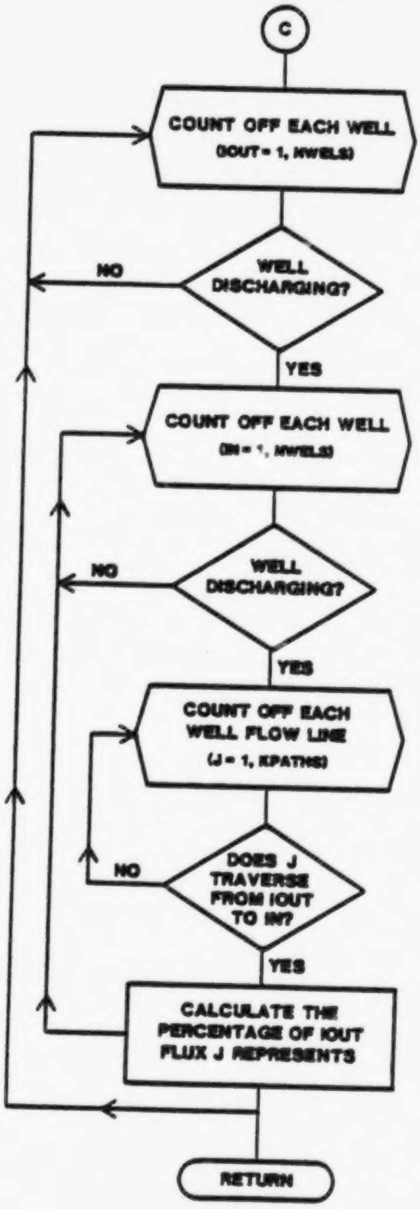
SUBROUTINE UNIFGR


A
COUNT OFF EACH AMBIENT FLOW LINE (1, NUFL)
DETERMINE INITIAL POSITION OF FLOW LINE
NO
MEDIA ANISOTROPIC?
YES
TRANSFORM LOCATION INTO ISOTROPIC MEDIA (CALL STRN)
CALCULATE ITS FLOW PATH (CALL RUNG)
B
RETURN

SUBROUTINE RUNG


B
COUNT OFF ITERATION (1, 499)
CALCULATE THE LOCATION OF THE FOLLOWING ITERATION BY EMPLOYING RUNG-KUTTA EQUATIONS (SEE TEXT)
YES
LOCATION WITHIN A WELL?
NO
YES
VELOCITY TOO GREAT?
NO
NO
NUMERICAL ERROR TOO LARGE?
YES
RETURN

SUBROUTINE WLDSTR


C
COUNT OFF EACH WELL
(IOUT = 1, NWELS)
NO
WELL DISCHARGING?
YES
COUNT OFF EACH WELL
(IN = 1, NWELS)
NO
WELL DISCHARGING?
YES
COUNT OFF EACH WELL FLOW LINE
(J = 1, KPATHS)
NO
DOES J TRAVERSE FROM IOUT TO IN?
YES
CALCULATE THE PERCENTAGE OF IOUT FLUX J REPRESENTS
RETURN

APPENDIX B

********************** POLLUTE LISTING ************************

```
      PROGRAM PETE(DATA=101B,OUTPUT=101B,TAPE5=DATA,TAPE6=OUTPUT,
     *TAPE99=0,TAPE7)
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A5/ XCIRC,YCIRC
      COMMON /A6/ TMY,TMX
      COMMON /A7/ KSTOR,KZ,KM
      COMMON /A8/ XPRIM,YPRIM,M
      COMMON /A9/ YTM,XTM
      COMMON /A10/ SXMIN,SXMAX,SYMIN,SYMAX
      COMMON /A11/ NWELS,NPTHS
      COMMON /A13/ XDIFF,YDIFF
      COMMON /A14/ SETYR,SETYL
      COMMON /A15/ UFDIST,NUFL
      COMMON /A16/ W,WOPT,WINC
      COMMON /A17/ VELOC
      COMMON /A18/ SXDIF,SYDIF
      COMMON /A19/ G
      COMMON /A20/ RINFL
      COMMON /A21/ YEARF,YINIT,XINIT,YFINI,XFINI
      COMMON /A22/ PI,QSUM
      COMMON /A23/ YEARS
      COMMON /A24/ K, KK
      COMMON /A25/ IORIG, IDEST
      COMMON /A26/ NPLOT
      COMMON /A27/ KPWEL
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL XIM(10,20), YIM(10,20)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XCIRC(21), YCIRC(21)
      REAL TMX(25,80), TMY(25,80)
      REAL IORIG(80), IDEST(80), YFINI(80), XFINI(80)
      REAL XPRIM(500), YPRIM(500)
      REAL YTM(80), XTM(80)
      REAL G(21)
      REAL YEARF(80), YINIT(80), XINIT(80)
      REAL YEARS(500)
      REAL KPWEL(20)
C
C
```

```
************************ POLLUTE LISTING *************************




C
C
C********************************************************************************
C
C
C                   ################
C                   ##            ##
C                   ##    INPUT   ##
C                   ##            ##
C                   ################
C
C
C     CARD 1 DELINEATES WHICH SPECIFIC DATA SETS WITHIN THE
C            ENTIRE DATA DECK WILL BE ACTIVATED.
C            A DATA SET CONTAINS A WELL FIELD CONFIGURATION
C            AND AQUIFER PARAMETERS.
C
C     CARD 2 TELLS US THE BOUNDARIES OF THE STUDY AREA.
C            X MIN, XMAX, YMIN, YMAX, NUFL   ARE ENTERED
C            IN RESPECTIVELY.  NUFL IS THE NUMBER OF UNIF
C            FLOW LINES TO BE TRACED OUT OVER THE ENTIRE
C            STUDY AREA.
C
C     CARD 3 DELINEATES THE TOTAL NUMBER OF WELLS, AND ALSO
C            THE TOTAL NUMBER OF WELL FLOW LINES TO BE TRACED
C            OVER THE ENTIRE STUDY AREA.  WELLS ARE LIMITED TO
C            20 MAXIMUM, AND WELL FLOW LINES TO 80 MAXIMUM.
C            FOR ZERO FLOW LINES, ENTER 1 . BOTH INPUTS ARE
C            INTEGERS.  ACTUAL FLOW LINES MAY BE ONE OR TWO LESS
C            THAN INPUTED FOR THEY ARE DIVIDED UP AMONG ALL THE WELLS
C    CARDS 4 ARE WELL CHARACTERISTICS.  FOR EACH WELL AN (X,Y)
C            COORDINATE IS ENTERED, THE RADIUS OF THE WELL,
C            DISCHARGE OF THE WELL, AND HEAD OF THE WELL.
C            IF EITHER HEAD OR DISCHARGE IS NOT KNOWN; ENTER 0.0
C
C     CARD 5 SETS AQUIFER PARAMETERS.  AVERAGE DEPTH OF AQUIFER,
C            POROSITY, UNIFORM GRADIENT, HYDRAULIC CONDUCTIVITY,
C            AND A BOUNDARY OF EQUAL HEAD. THE BOUNDARY OF EQUAL HEAD
C            IS GIVEN AS A LINEAR DISTANCE FROM THE ORIGIN.
C            NOTE: ALL UNITS MUST AGREE!
C
C     CARD 6 DETAILS THE THE DIRECTION OUT OF WHICH THE UNIFORM
C            FLOW FIELD IS COMING, THE OPTIONAL TIME INCREMENT,
C            AND THE DISTRIBUTION SIZE OF THE UNIFORM FLOW LINES.
C            FLOW FIELD DIRECTION WHERE;     0.0
C                                             I
C                                       270.0-*-90.0
C                                             I
```

```
C
C                                            180.0
C             THE OPTIONAL TIME INCREMENT MAY BE SET MANUALLY, OR
C             LEFT FOR THE MODEL TO SET AUTOMATICALLY. FOR AUTOMATIC
C             SETTING, ENTER 0.0 .  THE UNIFORM FLOW DISTRIBUTION
C             PARAMETER GIVES A FACTOR OVER WHICH THE UNIFORM FLOW
C             LINES WILL BE DISTRIBUTED OVER.  BY ENTERING 1.0, THE
C             DISTRIBUTION WILL BE THE SIZE OF THE Y-AXIS INSIDE THE
C             WINDOW.  2.0 WILL DOUBLE IT, 3.0 WILL TRIPLE IT, ETC.
C             THE DISTRIBUTION IS CENTERED ABOUT THE ORIGIN.  FOR THIS
C             PARAMETER, 3.0 SEEMS TO WORK WELL IN MOST CASES.
C
C      CARD 7  DETERMINES AQUIFER ANISOTROPY
C
C      CARD 8  IS THE NUMBER OF LINEAR AQUIFER BOUNDARIES (CARD 9).
C
C     CARDS 9  SETS THE SLOPE, Y INTERCEPT, AND TYPE OF AQUIFER
C              BOUNDARY.  AN IMPERMEABLE BOUNDARY IS DENOTED BY
C              1.0, AND AN EQUAL HEAD BOUNDARY IS DENOTED BY -1.0.
C
C      CARD 10 GIVE US THE BOUNDARIES FOR THE VARIOUS WINDOWS
C              WITHIN THE DATA SET. X MIN, X MAX, Y MIN, YMAX ARE
C              ENTERED IN RESPECTIVELY.  NPLOT CODE (BELOW) IS ALSO INPUT.
C
C      CARD 11 ----  NEXT DATA SET  ----
C
C
C      THE NPLOT CODE DICTATES THE PLOTTED OUTPUT
C      NPLOT CODE IS AS FOLLOWS:
C
C      CODE     FLOW/PIEZ      FLOW     ISOCHR     PIEZ      WELL DIST
C      ####     #########      ####     ######     ####      #########
C       -4          X            -         X         -           X
C       -3          X            -         -         -           X
C       -2          X            -         X         -           -
C       -1          X            -         -         -           -
C        0          -            X         -         -           -
C        1          -            X         -         X           -
C        2          -            X         X         X           -
C        3          -            X         -         X           X
C        4          -            X         X         X           X
C        5          -            X         X         -           -
C        6          -            X         X         -           X
C        7          -            X         -         -           X
C        8          -            -         -         X           -
C        9          -            -         -         -           X
C
C
```

********************** POLLUTE LISTING *************************

```
C
C                           ???????????????????????
C                           ??                   ??
C                           ??   INPUT EXAMPLE   ??
C                           ??                   ??
C                           ???????????????????????
C
C      CARD 1  1,1             -ONE DATA SET ONLY
C      CARD 2  -1000.,9000.,-5000.,2000.,20
C      CARD 3  3,15
C     CARDS 4  0.,0.,100.,0.,24.
C        "      1000.,-2688.,1000000.,0.
C        "     2000.,2000.,1500000.,0.
C     CARD 5  70.,.2,.0095.,10950.,20000.
C     CARD 6  270.,0.,3.
C     CARD 7  3.,1.
C     CARD 8  1
C     CARD 9  -1000.,10000000.,-1.  EQUAL HEAD BNDY AT X = 10000
C    CARD 10  -1000.,8000.,-5000.,2000.
C
C
C******************************************************************************
C
C
      WRITE(6,1000)
 1000 FORMAT( 1X,"ENTER; DATA SET # START, DATA SET # END"/
     *         6X,"FOR ONLY ONE DATA SET, ENTER; 1,1")
      READ(5,*)NUMY,NIMY
      DO 999 IJK = 1,NIMY
      WRITE(6,1005) IJK
 1005 FORMAT( 1X,"DATA SET ",I3)
      WRITE(6,1010)
 1010 FORMAT( 1X/1X,"ENTER FOR ENTIRE STUDY AREA;"/
     *          "X MIN, X MAX, Y MIN, Y MAX, NUM UNIF FLOW LINES (INT)")
      READ (5,*) SXMIN,SXMAX,SYMIN,SYMAX, NUFL
      IF(NUFL.GE.2) NUFL = NUFL - 1
C
C
C
C
      CALL INITIZ
C
      CALL INPUT1
C
C
      WRITE(6,1015)
 1015 FORMAT( 1X/1X,"ENTER: ANISOTROPY ALONG   X-AXIS,YAXIS"/1X,
     *        "EXAMPLES: IF ISOTROPIC ENTER   1.,1."/1X,
     *    "                IF ANISOTROPIC ALONG X-AXIS BY A FACTOR OF THREE,"/
     * 1X,"                   ENTER   3.,1.")
      READ(5,*) ANISX, ANISY
      NTRX = 0
      NTRY = 0
      IF (ANISX .NE. 1.) NTRX = 3
      IF (ANISY .NE. 1.) NTRY = 3
C
C   ...INPUT DATA NEEDED FOR ANY BOUNDARYS ...
      WRITE(6,1020)
 1020 FORMAT(1X,"ENTER NUMBER OF BOUNDARIES (ZERO=0)")
      READ(5,*) IBND
      IF (IBND .EQ. 0) GO TO 15
      DO 5 K1 = 1,IBND
      WRITE(6,1025)
 1025 FORMAT(1X,"BOUNDARIES ARE LINEAR; ENTER: SLOPE(WHERE SLOPE DOES",
     * " NOT EQUAL ZERO)"/1X," ENTER: Y INTERCEPT"/
     * 1X,"ENTER: EITHER 1., OR -1., FOR IMPERMIABLE BNDRY OR STREAM")
      READ(5,*) SLOPE(K1), BINCPT(K1) , BNDRY(K1)
    5 CONTINUE
      DO 10 I1 = 1,IBND
      DO 10 I2 = 1,NWELS
      CALL IMAGE(SLOPE(I1),BINCPT(I1),X(I2),Y(I2),XIM(I1,I2),YIM(I1,I2))
   10 CONTINUE
   15 WRITE(6,1030)
 1030 FORMAT(1X,"ENTER: MIN X, MAX X, MIN Y, MAX Y (FOR WINDOW)",
     */1X,"AND NPLOT CODE"///)
      READ(5,*) XMIN,XMAX,YMIN,YMAX,NPLOT
      IF(NTRX.EQ.0) GO TO 20
      CALL VART(SXMIN,SXMAX,NTRX,AFORX,BFORX,ARETX,BRETX,ANISY,ANISX)
   20 IF(NTRY.EQ.0) GO TO 25
      CALL VART(SYMIN,SYMAX,NTRY,AFORY,BFORY,ARETY,BRETY,ANISX,ANISY)
   25 CALL STRN(NTRX,AFORX,BFORX,NWELS,X,X)
      CALL STRN(NTRY,AFORY,BFORY,NWELS,Y,Y)
      DO 30 I1=1,IBND
      DO 30 I2=1,NWELS
      CALL STRN(NTRY,AFORY,BFORY,1,YIM(I1,I2),YIM(I1,I2))
   30 CALL STRN(NTRX,AFORX,BFORX,1,XIM(I1,I2),XIM(I1,I2))
C
C
      IF(IJK.LT.NUMY) GO TO 999
      IF(NWELS.EQ.0) GO TO 45
      DO 35 I=1,NWELS
      IF(Q(I).EQ.0.0 .AND.HEAD(I).NE.0.0) Q(I) = 2.*PI*HYDRK
     *         *DEPTH*(HEAD(I))/ALOG(RINFL/RWELL(I))
      HEAD(I)=Q(I)*ALOG(RINFL/RWELL(I))/(2.*PI*HYDRK*DEPTH)
      IF(Q(I).GT.0.0) QSUM = QSUM+Q(I)
   35 CONTINUE
```

```
      WRITE(6,1035)
 1035 FORMAT(1H1//1X,4HWELL,T13,6HXCOORD,T27,6HYCOORD
     *        ,T41,6HRADIUS,T52,10HLOCAL HEAD,T69,9HDISCHARGE//)
      DO 40 I=1,NWELS
      WRITE(6,1040)I,X(I),Y(I),RWELL(I),HEAD(I),Q(I)
 1040 FORMAT(3X,I2,T11,F8.0,T25,F8.0,T40,F7.1,T50,F9.2,T64,F14.2)
   40 CONTINUE
C
C
C
C
C      SET PLOT PARAMETERS
C
   45 CALL PLOTPA
C
      IF(NPLOT .EQ. 8) GO TO 80
      IF((NPLOT.GE.-4) .AND. (NPLOT.LE.-1)) CALL PIEZ
C
C
C      *   MARK OFF WELL   *
C
      CALL WELCIR
C
C
C
C      DETERMINE TIME ITERATION
C
C
      CALL ITERAT
C
C      SET UNIFORM FLOW GRADIENT LINES
C
      CALL UNIFGR
C
C
C
C
   50 C = .000004164
      KZ = 0
      START = 8.84
C
C
      DO 75 K=1,NWELS
C
       IF(Q(K).LE.0) GO TO 75
C
C
C
```

```
C
C
C
      ZPWEL = FLOAT(NPTHS)*Q(K)/QSUM
      IF(ZPWEL.LT.1.) GO TO 75
      KPWEL(K) = IFIX(ZPWEL)
      KPWELA = KPWEL(K)
      RSET = 2.*PI/FLOAT(KPWELA)
C
C
       WRITE(6,1045) Q(K),KPWELA
      KMBEG = KM + 1
      DO 70 J=1,KPWELA
      KZ = KZ + 1
C
C
      RADNS = RSET*FLOAT(J)
       XPRIM(1) = RWELL(K) * COS(RADNS) + X(K)
       YPRIM(1) = RWELL(K) * SIN(RADNS) + Y(K)
C
C
C
C
      KM = KM + 1
C
      CALL RUNG(XPRIM,YPRIM,NBND,I,M,W,1)
      WRITE(6,1047)XPRIM(1),YPRIM(1),M
 1045 FORMAT(1X,"WELL RECHARGE = ",F16.2,10X,I3," FLOW PATHS"/)
 1047 FORMAT(1X/1X,"INITIAL LOCATION IS (",F10.2,",",F10.2,")",10X,
     *        I3," ITERATIONS")
      IF (NBND) 60,60,55
C
C
C
C
  55  WRITE(6,1050)J,K,NBND,YEARS(M)
 1050 FORMAT(1X,5HPATH ,I2,9H OF WELL ,I2,17H ARRIVED AT WELL ,
     *        I2,4H IN ,F7.2,6H YEARS)
C
      IORIG(KM) = K
      IDEST(KM) = NBND
C
      CALL ISOCHR
C
      GO TO 65
C
C
C
```

```
C
   60 WRITE(6,1055)J,K,XPRIM(M),YPRIM(M),YEARS(M)
 1055 FORMAT(1X,5HPATH ,I2,9H OF WELL ,I2," ARRIVED AT (",F8.2,
     *  ",",F8.2,")  IN",F7.2," YEARS")
C
      IORIG(KM) = K
      IDEST(KM) = 999
C
C
      CALL ISOCHR
C
C
   65 CONTINUE
   70 CONTINUE
C
      CALL CUMFLOW(XINIT,YINIT,KMBEG,KM,K)
C
C
C
C
C
   75 CONTINUE
C
C
C
C
C
      WRITE(6,1065) W
       WTMPL = W * 20.
       WRITE(6,1060) WTMPL
 1060 FORMAT( 1X//1X,"ISOCHRONE PLOTTED EVERY ",F7.2," YEARS")
 1065 FORMAT(///1X,F17.3,1X,28HYEARS, IS THE TIME INCREMENT)
      CALL FRAME
      IF(QSUM.LE.0) GO TO 100
C
C
C      MAP OUT PIEZIOMETRIC SURFACE
C
C
      IF((NPLOT.GE.1) .AND. (NPLOT.LE.4)) GO TO 80
      GO TO 85
   80 CALL SETW(.27,.87,SETYL,SETYR,XMIN,XMAX,YMIN,YMAX,1)
      CALL LABMOD(6H(F8.0),6H(F8.0),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,XMIN,YMIN)
      CALL PIEZ
      CALL WELCIR
      CALL FRAME
      IF(NPLOT .EQ. 8) GO TO 999
```

```
C
C
C     THIS PROGRAM TIME PLOT IS SET FOR A 80 PATH MAXIMUM
C     AND A 12 TIME INCREMENT MAXIMUM
C
C
C
C
C
   85 IF((NPLOT.EQ.2) .OR. (NPLOT.EQ.4)) GO TO 90
      IF((NPLOT.EQ.-2) .OR. (NPLOT.EQ.-4)) GO TO 90
      IF ((NPLOT.EQ.6) .OR. (NPLOT.EQ.5)) GO TO 90
      GO TO 100
   90 CALL SETW(.27,.87,SETYL,SETYR,XMIN,XMAX,YMIN,YMAX,1)
      CALL LABMOD(6H(F8.0),6H(F8.0),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,XMIN,YMIN)
      DO 95 I=1,25
      DO 95 J=1,KM
      XPNT = TMX(I,J)
      YPNT = TMY(I,J)
      IF((XPNT.GT.XMAX) .OR. (XPNT.LT.XMIN)) GO TO  95
      IF((YPNT.GT.YMAX) .OR. (YPNT.LT.YMIN)) GO TO 95
      IF((XPNT.EQ.0.0) .AND. (YPNT.EQ.0.0)) GO TO 95
      CALL POINT(XPNT,YPNT)
   95 CONTINUE
C
C
C     *  MARK OFF WELL ON ISOCHRONE PLOT  *
C
       CALL WELCIR
C
C
      CALL FRAME
  100 CONTINUE
      CALL WLDSTR
  999 CONTINUE
      STOP
      END
      SUBROUTINE RUNG(XPRIM,YPRIM,NBND,I,M,W,IFLAG)
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A11/ NWELS,NPTHS
      COMMON /A19/ G
      COMMON /A20/ RINFL
      COMMON /A22/ PI,QSUM
      COMMON /A23/ YEARS
      COMMON /A26/ NPLOT
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL XIM(10,20), YIM(10,20)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XPRIM(500), YPRIM(500)
      REAL YEARS(500)
      REAL G(21)
      REAL K1, K2, K3, K4
      DO 5 J=1,NWELS
      G(J) = (Q(J)/(2.*PI*DEPTH*POROS))
   5  CONTINUE
      CALL STRN(NTRX,AFORX,BFORX,1,XMIN,XMIN)
      CALL STRN(NTRX,AFORX,BFORX,1,XMAX,XMAX)
      CALL STRN(NTRY,AFORY,BFORY,1,YMIN,YMIN)
      CALL STRN(NTRY,AFORY,BFORY,1,YMAX,YMAX)
      G(21) = HYDRK*U/POROS
C
C
C      *********************************************************
C      *                                                       *
C      *   THIS SUBROUTINE CALCULATES FLOW LINES BY USING      *
C      *   THE RUNGE-KUTTA METHOD.                             *
C      *                                                       *
C      *********************************************************
C
C
C
      ICYC = 0
  10  DO 35 I = 1,499
      M = I+1
      YEARS(M) = YEARS(I) + W
      XD = XPRIM(I)
      YD = YPRIM(I)
      K1 = F1(XD,YD)
      C1 = F2(XD,YD)
      K2 = F1(XD+W/2.*K1,YD+W/2.*C1)
      C2 = F2(XD+W/2.*K1,YD+W/2.*C1)
      K3 = F1(XD+W/2.*K2,YD+W/2.*C2)
      C3 = F2(XD+W/2.*K2,YD+W/2.*C2)
      K4 = F1(XD+W*K3,YD+W*C3)
      C4 = F2(XD+W*K3,YD+W*C3)
      XPRIM(M) = XPRIM(I) + W/6.*(K1 +2.*K2 + 2.*K3 + K4)
      YPRIM(M) = YPRIM(I) + W/6.*(C1 +2.*C2 + 2.*C3 + C4)
      ZZC = ABS((C3-C2)/(C2-C1))
      ZZK = ABS((K3-K2)/(K2-K1))
C
      IF((I.LT.7).AND.(ICYC.EQ.0)) GO TO 35
      IF((IFLAG.GT.1) .AND. (ICYC.GT.0)) GO TO 13
      M2 = M/2
      M21 = M2 + 1
      VELOC = SQRT((XPRIM(M21) - XPRIM(M2))**2
     *         +   (YPRIM(M21) - YPRIM(M2))**2)/W
   13 NM = 1
      DO 30 N=1,NWELS
      IF (IBND.EQ.0) GO TO 20
      DO 15 IB = 1,IBND
   15 IF(((XPRIM(I)-X(N))**2 + (YPRIM(I)-Y(N))**2) .GE.
     * ((XPRIM(I)-XIM(IB,N))**2 + (YPRIM(I)-YIM(IB,N))**2)) GO TO 40
   20 IF (Q(N).GE.-.99) GO TO 30
      IF(SQRT((XPRIM(I)-X(N))**2+(YPRIM(I)-Y(N))**2)
     *    .GT.(VELOC*W*8.0+RWELL(N)))GO TO 30
      IF((ZZC.GE.2.0) .AND. (ZZK.GE.2.0)) GO TO 25
      IF((SQRT((XPRIM(I)-X(N))**2+(YPRIM(I)-Y(N))**2)).LE.
     *     (RWELL(N))) GO TO 50
      IF((2.75*VELOC*W).GE.SQRT((XPRIM(M)-XPRIM(I))**2
     *   +(YPRIM(M)-YPRIM(I))**2)) GO TO 30
   25 IF(((XPRIM(I)-X(N))**2 + (YPRIM(I)-Y(N))**2) .LT.
     *  ((XPRIM(I)-X(NM))**2 + (YPRIM(I)-Y(NM))**2)) NM = N
   30 CONTINUE
      IF(NM.NE.1) GO TO 45
      IF ((IFLAG.EQ.1) .OR. (NPLOT.GT.7)) GO TO 35
      CALL STRN(NTRX,ARETX,BRETX,1,XPRIM(M),XPRIMM)
      CALL STRN(NTRY,ARE,BRETY,1,YPRIM(M),YPRIMM)
      CALL STRN(NTRX,ARETX,BRETX,1,XPRIM(I),XPRIMI)
      CALL STRN(NTRY,ARETY,BRETY,1,YPRIM(I),YPRIMI)
      CALL LINEW(XPRIMI,YPRIMI,XPRIMM,YPRIMM)
C
   35 CONTINUE
      ICYC = ICYC + 1
      IF (ICYC .GE. IFLAG) GO TO 40
      XPRIM(1) = XPRIM(M)
      YPRIM(1) = YPRIM(M)
      GO TO 10
   40 NBND = -1
      GO TO 60
   45 N = NM
   50 NBND = N
      M = I
      GO TO 60
   55 NBND = 0
   60 CALL STRN(NTRX,ARETX,BRETX,1,XMIN,XMIN)
      CALL STRN(NTRX,ARETX,BRETX,1,XMAX,XMAX)
      CALL STRN(NTRY,ARETY,BRETY,1,YMIN,YMIN)
      CALL STRN(NTRY,ARETY,BRETY,1,YMAX,YMAX)
      RETURN
C
      END
      FUNCTION F1(XD,YD)
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A11/ NWELS,NPTHS
      COMMON /A19/ G
      COMMON /A20/ RINFL
       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XIM(10,20), YIM(10,20)
      REAL G(21)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
C
C
C      *****************************************************
C      *                                                   *
C      *  FUNCTION F1 IS THE X COMPONENT OF THE DIFFERENTIAL *
C      *  EQUATION DESCRIBING A FLOW LINE.                  *
C      *                                                   *
C      *****************************************************
C
C
C
      F1 = 0.
      F1 = G(21)*COS(FLANG)  + F1
      DO 10 J=1,NWELS
      YY = (YD-Y(J))**2
      XX = (XD-X(J))**2
      XY2 = XX + YY
      UNIT = 1.0
      IF(RINFL .LE. SQRT(XY2)) UNIT = 0.0
      F1=(G(J)*(XD-X(J))/XY2)*UNIT
     *     +F1
      IF (IBND.EQ.0) GO TO 10
      DO 5 L = 1,IBND
      XX2 = (XD-XIM(L,J))**2
      YY2 = (YD-YIM(L,J))**2
      XY4 = XX2 + YY2
      UNIT = 1.0
      IF(RINFL .LE. SQRT(XY4)) UNIT = 0.0
      F1 = (G(J)*BNDRY(L)*(XD-XIM(L,J))/XY4)*UNIT + F1
```

```
  5   CONTINUE
 10   CONTINUE
      RETURN
      END
      FUNCTION F2(XD,YD)
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A11/ NWELS,NPTHS
      COMMON /A19/ G
      COMMON /A20/ RINFL
       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL XIM(10,20), YIM(10,20)
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL G(21)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
C
C
C      ******************************************************
C      *                                                    *
C      *  FUNCTION F2 IS THE Y COMPONENT OF THE DIFFERENTIAL *
C      *  EQUATION DESCRIBING A FLOW LINE.                  *
C      *                                                    *
C      ******************************************************
C
C
C
      F2 = 0.
      F2 = -G(21)*SIN(FLANG) + F2
      DO 10 J=1,NWELS
      YY = (YD-Y(J))**2
      XX = (XD-X(J))**2
      XY2 = XX + YY
      UNIT = 1.0
      IF(RINFL .LE. SQRT(XY2)) UNIT = 0.0
      F2=(G(J)*(YD-Y(J))/XY2) * UNIT
     *      +F2
      IF (IBND.EQ.0) GO TO 10
      DO 5 L = 1,IBND
      XX2 = (XD-XIM(L,J))**2
      YY2 = (YD-YIM(L,J))**2
      XY4 = XX2 + YY2
      UNIT = 1.0
      IF(RINFL .LE. SQRT(XY4)) UNIT = 0.0
      F2 = (G(J)*BNDRY(L)*(YD-YIM(L,J))/XY4)*UNIT + F2
  5   CONTINUE
 10   CONTINUE
      RETURN
      END
      SUBROUTINE INITIZ
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A6/ TMY,TMX
      COMMON /A7/ KSTOR,KZ,KM
      COMMON /A8/ XPRIM,YPRIM,M
      COMMON /A19/ G
      COMMON /A22/ PI,QSUM
      COMMON /A23/ YEARS
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XPRIM(500), YPRIM(500)
      REAL G(21)
      REAL YEARS(500)
      REAL TMX(25,80), TMY(25,80)
C
C
C      *****************************************************
C      *                                                   *
C      *   VARIABLES ARE INITIALIZED TO ZERO.              *
C      *                                                   *
C      *****************************************************
C
C
      M = 0
      KZ = 0
      KSTOR = 0
      PI = 3.141592654
      DO 5 I=1,500
      YEARS(I)=0.0
      YPRIM(I)=0.0
      XPRIM(I) = 0.0
    5 CONTINUE
      DO 10 I=1,20
      HEAD(I) = 0.0
      Q(I) = 0.0
      RWELL(I) = 0.0
      X(I) = 0.0
      Y(I) = 0.0
   10 CONTINUE
      DO 15 I = 1,25
      DO 15 J = 1,80
      TMX(I,J) = 0.
      TMY(I,J) = 0.
   15 CONTINUE
C
C
      KM = 0
      YEARS(1) = 0.0
```

```
C
C
      QSUM = 0.
C
      RETURN
      END
      SUBROUTINE INPUT1
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A10/ SXMIN,SXMAX,SYMIN,SYMAX
      COMMON /A11/ NWELS,NPTHS
      COMMON /A15/ UFDIST,NUFL
      COMMON /A16/ W,WOPT,WINC
      COMMON /A20/ RINFL
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
C
C
C      **************************************************
C      *                                                *
C      *  SUBROUTINE INPUT1 READS MUCH OF THE INPUT     *
C      *  DATA.                                         *
C      *                                                *
C      **************************************************
C
C
C
      WRITE(6,2505)
 2505 FORMAT(1X,41HINPUT THE TOTAL NUMBER OF WELLS(01 TO 20)/1X,
     * 47H AND TOTAL NUMBER OF WELL-FLOW LINES (01 TO 80))
      READ(5,*) NWELS,NPTHS
      IF(NWELS.EQ.0) GO TO 10
      DO 5 I=1,NWELS
      WRITE(6,2510) I
 2510 FORMAT(1X,5HWELL-,I2//1X,51HENTER: XCOORD, YCOORD, WELL RADIUS, DI
     *SCHARGE, HEAD/11X,1HL,7X,1HL,10X,1HL,7X,8H(L**3)/T,4X,1HL//
     *          1X,37HIF DISCHARGE IS KNOWN, SET HEAD = 0.0)
      READ(5,*) X(I), Y(I), RWELL(I), Q(I), HEAD(I)
    5 CONTINUE
   10 WRITE(6,2515)
 2515 FORMAT(1X,38HENTER: AVG DEPTH, POROSITY, UNIF GRAD,,
     *          32H HYDR K, AVG RADIUS OF INFLUENCE/
     *          13X,1HL,18X,3HL/L,5X,3HL/T,17X,1HL)
      READ(5,*) DEPTH, POROS, U, HYDRK, RINFL
      WRITE(6,2520)
 2520 FORMAT(1X,38HENTER; ANGLE OF UNIFORM FLOW (DEGREES)/
     *          1X,32HN= 0.0, E= 90., W= 270., S= 180./
     *  1X,48HENTER; OPTIONAL TIME INCREMENT (0.0 = AUTOMATIC))
```

```
C
C
      QSUM = 0.
C
      RETURN
      END
      SUBROUTINE INPUT1
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A10/ SXMIN,SXMAX,SYMIN,SYMAX
      COMMON /A11/ NWELS,NPTHS
      COMMON /A15/ UFDIST,NUFL
      COMMON /A16/ W,WOPT,WINC
      COMMON /A20/ RINFL
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
C
C
C     ************************************************
C     *                                              *
C     *   SUBROUTINE INPUT1 READS MUCH OF THE INPUT  *
C     *   DATA.                                      *
C     *                                              *
C     *                                              *
C     ************************************************
C
C
C
      WRITE(6,2505)
 2505 FORMAT(1X,41HINPUT THE TOTAL NUMBER OF WELLS(01 TO 20)/1X,
     * 47H AND TOTAL NUMBER OF WELL-FLOW LINES (01 TO 80))
      READ(5,*) NWELS,NPTHS
      IF(NWELS.EQ.0) GO TO 10
      DO 5 I=1,NWELS
      WRITE(6,2510) I
 2510 FORMAT(1X,5HWELL-,I2//1X,51HENTER: XCOORD, YCOORD, WELL RADIUS, DI
     *SCHARGE, HEAD/11X,1HL,7X,1HL,10X,1HL,7X,8H(L**3)/T,4X,1HL//
     *      1X,37HIF DISCHARGE IS KNOWN, SET HEAD = 0.0)
      READ(5,*) X(I), Y(I), RWELL(I), Q(I), HEAD(I)
    5 CONTINUE
   10 WRITE(6,2515)
 2515 FORMAT(1X,38HENTER: AVG DEPTH, POROSITY, UNIF GRAD,,
     *      32H HYDR K, AVG RADIUS OF INFLUENCE/
     *      13X,1HL,18X,3HL/L,5X,3HL/T,17X,1HL)
      READ(5,*) DEPTH, POROS, U, HYDRK, RINFL
      WRITE(6,2520)
 2520 FORMAT(1X,38HENTER; ANGLE OF UNIFORM FLOW (DEGREES)/
     *      1X,32HN= 0.0, E= 90., W= 270., S= 180./
     *  1X,48HENTER; OPTIONAL TIME INCREMENT (0.0 = AUTOMATIC))
```

```
      WRITE(6,2525)
 2525 FORMAT(1X,"ENTER; UNIF FLOW DIST SIZE, 3.0=SUGESTED")
      READ(5,*) ANGLE, WOPT, UFDIST
C
C       *   ANGLE IS CHANGED INTO MATHMATICAL COORDINATES    *
C       *   WHERE EAST = 0.0 DEGREES. THEN CHANGED INTO      *
C       *   RADIANS                                          *
C
      ANGLE = 270.-ANGLE
      FLANG = (-ANGLE/57.29577951)
      RTANG =    - FLANG
C
      RETURN
      END
      SUBROUTINE PLOTPA
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A13/ XDIFF,YDIFF
      COMMON /A14/ SETYR,SETYL
      COMMON /A26/ NPLOT
C
C
C       **************************************************
C       *
C       *                                                *
C       *  EXTENT OF PLOTTED WINDOWS ARE DEFINED SO THAT  *
C       *  THE X AXIS WILL BE IN SCALE WITH THE Y AXIS.   *
C       *                                                *
C       **************************************************
C
C
C
  5   XDIFF = (XMAX - XMIN)
      YDIFF = (YMAX - YMIN)
      SETY = .6*YDIFF/XDIFF
      IF(SETY.LT.1.0) GO TO 10
      XMIN = XMIN - XDIFF/5.
      GO TO 5
 10   SETYR = .5 + SETY/2.
      SETYL = .5 - SETY/2.
      IF(NPLOT.GT.7)GO TO 15
      CALL SETW(.27,.87,SETYL,SETYR,XMIN,XMAX,YMIN,YMAX,1)
      CALL LABMOD(6H(F8.0),6H(F8.0),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,XMIN,YMIN)
 15   RETURN
      END
      SUBROUTINE WELCIR
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A5/ XCIRC,YCIRC
```

```
C      *                                                    *
C      *  SUBROUTINE CUMFLOW DETERMINES THE PERCENTAGE OF   *
C      *  WELL FLOW EACH FLOW LINE REPRESENTS.              *
C      *                                                    *
C      ******************************************************
C
C
       SMALL = .000001
       NSMAL =-.000001
       WRITE(6,3100)
 3100  FORMAT(1X//1X)
       DO 25 J = KMBEG,KM
       Y = YINIT(J)
       X = XINIT(J)
       CUMQ(J) = (U * DEPTH * HYDRK/Q(K))
      *   * ((Y-YWELL(K))*COS(FLANG) + (X-XWELL(K))*SIN(FLANG))
       DO 5 I = 1,NWELS
       XXW = (X-XWELL(K)) - (XWELL(I)-XWELL(K))
       YWW = (Y-YWELL(K)) - (YWELL(I)-YWELL(K))
       RWXW = RWELL(K) - XWELL(I)
       IF(XXW.LT.SMALL .AND. XXW.GE.0)XXW = SMALL
       IF(XXW.GT.NSMAL .AND. XXW.LE.0)XXW = NSMAL
       IF(RWXW.LT.SMALL .AND. RWXW.GE.0)RWXW = SMALL
       IF(RWXW.GT.NSMAL .AND. RWXW.LE.0)RWXW = NSMAL
       CUMQ(J) = Q(I)/(Q(K)*2.*PI) * (ATAN2(YWW,XXW)
      *         -  ATAN2((YWELL(K)-YWELL(I)),RWXW))
      *     + CUMQ(J)
 5     CONTINUE
       IF(IBND.EQ.0) GO TO 15
       DO 10 I = 1,NWELS
       DO 10 IB = 1,IBND
       XXW = (X-XWELL(K)) - (XIM(IB,I)-XWELL(K))
       YWW = (Y-YWELL(K)) - (YIM(IB,I)-YWELL(K))
       RWXW = RWELL(K) - XIM(IB,I)
       IF(XXW.LT.SMALL .AND. XXW.GE.0)XXW = SMALL
       IF(XXW.GT.NSMAL .AND. XXW.LE.0)XXW = NSMAL
       IF(RWXW.LT.SMALL .AND. RWXW.GE.0)RWXW = SMALL
       IF(RWXW.GT.NSMAL .AND. RWXW.LE.0)RWXW = NSMAL
       CUMQ(J) = BNDRY(IB)*Q(I)/(Q(K)*2.*PI) * (ATAN2(YWW,XXW)
      *      -  ATAN2((YWELL(K)-YIM(IB,I)),RWXW))
      *     + CUMQ(J)
 10    CONTINUE
 15    IF(CUMQ(J).GE.0.)GO TO 17
       CUMQ(J) = 1. + CUMQ(J)
       GO TO 15
 17    IF(CUMQ(J).LE.1.) GO TO 20
       CUMQ(J) = CUMQ(J) - 1.
       GO TO 17
      COMMON /A11/ NWELS,NPTHS
      COMMON /A22/ PI,QSUM
      COMMON /A26/ NPLOT
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XCIRC(21), YCIRC(21)
C
C
C      ****************************************************
C      *                                                  *
C      *  SUBROUTINE WELCIR REPRESENTS WELLS BY DRAWING   *
C      *  CIRCLES AT THE PROPER LOCATIONS.                *
C      *                                                  *
C      ****************************************************
C
C
C
C
      IF(NPLOT.GT.7) RETURN
      CALL STRN(NTRX,ARETX,BRETX,NWELS,X,X)
      CALL STRN(NTRY,ARETY,BRETY,NWELS,Y,Y)
      DO 10 I = 1,NWELS
      IF ((X(I).GE.XMAX) .OR. (X(I).LE.XMIN)) GO TO 10
      IF ((Y(I).GE.YMAX) .OR. (Y(I).LE.YMIN)) GO TO 10
      DO 5 IC = 1,20
      XCIRC(IC) = RWELL(I)*COS(FLOAT(IC)*2.*PI/20.)+X(I)
      YCIRC(IC) = RWELL(I)*SIN(FLOAT(IC)*2.*PI/20.)+Y(I)
    5 CONTINUE
      XCIRC(21) = XCIRC(1)
      YCIRC(21) = YCIRC(1)
      CALL CURVEW(XCIRC,YCIRC,21)
   10 CONTINUE
      CALL STRN(NTRX,AFORX,BFORX,NWELS,X,X)
      CALL STRN(NTRY,AFORY,BFORY,NWELS,Y,Y)
      RETURN
      END
      SUBROUTINE ITERAT
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A11/ NWELS,NPTHS
      COMMON /A16/ W,WOPT,WINC
      COMMON /A17/ VELOC
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
C
```

```
********************** POLLUTE LISTING *************************
```

```
C
C      **************************************************
C      *                                                *
C      *  THE ITERATION INTERVAL IS CALCULATED IF IT IS *
C      *  NOT INPUT.                                    *
C      *                                                *
C      **************************************************
C
C
C
      VELOC = HYDRK * U/POROS
      W = ABS((XMAX-XMIN)/(VELOC*250.))
      TRUNC = 1.
      IF(WOPT.GT.0)TRUNC = W/WOPT
      IF(WOPT.GT.0)W=WOPT
      WRITE(6,2805) NWELS
 2805 FORMAT(1X//1X,"THERE ARE ",I3,
     *     " PUMPING AND/OR RECHARGING WELLS"//)
C
      RETURN
      END
      SUBROUTINE UNIFGR
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A3/ XMIN,XMAX,YMIN,YMAX
      COMMON /A4/ FLANG,RTANG,TRUNC
      COMMON /A8/ XPRIM,YPRIM,M
      COMMON /A10/ SXMIN,SXMAX,SYMIN,SYMAX
      COMMON /A11/ NWELS,NPTHS
      COMMON /A15/ UFDIST,NUFL
      COMMON /A16/ W,WOPT,WINC
      COMMON /A18/ SXDIF,SYDIF
      COMMON /A19/ G
      COMMON /A20/ RINFL
      COMMON /A22/ PI,QSUM
      COMMON /A23/ YEARS
      COMMON /A24/ K, KK
      COMMON /A26/ NPLOT
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL XPRIM(500), YPRIM(500)
      REAL G(21)
      REAL YEARS(500)
C
C
```

```
C      ************************************************************
C      *                                                          *
C      *  SUBROUTINE UNIFGR LOCATES THE ORIGINATING               *
C      *  LOCATIONS OF ANY AMBIENT FLOW LINES.                    *
C      *                                                          *
C      ************************************************************
C
C
C
      SXDIF = SXMAX - SXMIN
      SYDIF = SYMAX - SYMIN
      IF(NUFL.LE.0)GO TO 10
      IF(NPLOT.GT.7)GO TO 10
      NUFL1 = NUFL + 1.
      YDIF3 = UFDIST*SYDIF
      YYMIN = 0. - YDIF3/2.
      DO 5 KK=1,NUFL1
      WRITE(6,*) KK
      XPRIM(1) = (-SQRT(SXDIF**2 + SYDIF**2))*COS(RTANG) +
     *        (YYMIN+YDIF3*(FLOAT(KK)-1.)/FLOAT(NUFL))*SIN(RTANG)
      YPRIM(1) =(YYMIN+YDIF3*(FLOAT(KK)-1.)/FLOAT(NUFL))*COS(RTANG)
     *        - (-SQRT(SXDIF**2 + SYDIF**2))*SIN(RTANG)
      CALL STRN(NTRX,AFORX,BFORX,1,XPRIM(1),XPRIM(1))
      CALL STRN(NTRY,AFORY,BFORY,1,YPRIM(1),YPRIM(1))
      CALL RUNG(XPRIM,YPRIM,NBND,I,M,W,3)
    5 CONTINUE
   10 RETURN
      END
      SUBROUTINE ISOCHR
      COMMON /A6/ TMY,TMX
      COMMON /A7/ KSTOR,KZ,KM
      COMMON /A8/ XPRIM,YPRIM,M
      COMMON /A21/ YEARF,YINIT,XINIT,YFINI,XFINI
      COMMON /A23/ YEARS
      COMMON /A26/ NPLOT
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL TMX(25,80), TMY(25,80)
      REAL XFINI(80),YFINI(80)
      REAL XPRIM(500), YPRIM(500)
      REAL YEARF(80), YINIT(80), XINIT(80)
      REAL YEARS(500)
C
C
C      ************************************************************
C      *                                                          *
```

```
C        * PLOTS FLOW LINES AND STORES ISOCHRONAL LOCATIONS *
C        *                                                  *
C        ****************************************************
C
C
C
      YINIT(KM) = YPRIM(1)
      XINIT(KM) = XPRIM(1)
      CALL STRN(NTRX,ARETX,BRETX,M,XPRIM,XPRIM)
      CALL STRN(NTRY,ARETY,BRETY,M,YPRIM,YPRIM)
      IF(KSTOR. GE.KZ) GO TO 10
      IF(NPLOT.GT.7) GO TO 5
      CALL CURVEW(XPRIM,YPRIM,M)
    5 KSTOR = KSTOR + 1
   10 CONTINUE
C
C        ...WE LOOK FOR THE NEXT TO LAST POINT, JUST IN CASE
C        THE LAST POINT IS A NUMERICAL ERROR        .
C
      XFINI(KM) = XPRIM(M-1)
      YFINI(KM) = YPRIM(M-1)
C
      YEARF(KM) = YEARS(M)
      KTM = 0
      DO 15 JTIME=21,M,20
      KTM = KTM + 1
      TMY(KTM,KM) = YPRIM(JTIME)
      TMX(KTM,KM) = XPRIM(JTIME)
   15 CONTINUE
      RETURN
      END
      SUBROUTINE CUMFLOW(XINIT,YINIT,KMBEG,KM,K)
      COMMON /A1/ XWELL,YWELL,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A4/ FLANG, RTANG, TRUNC
      COMMON /A11/ NWELS,NPATHS
      COMMON /A22/ PI,QSUM
      COMMON /B2/ CUMQ
       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL XIM(10,20), YIM(10,20)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
      REAL XWELL(20),YWELL(20),RWELL(20),Q(20),HEAD(20)
      REAL XINIT(80), YINIT(80)
      REAL CUMQ(80)
C
C
C     *******************************************************
```

```
      IPOINT(KOUNT) = J
      YEARFA(KOUNT) = YEARF(J)
      J1 = J+1
      J2 = J-1
      IF(J.EQ.KM)J1 = 1
      IF(J.EQ.1)J2 = KM
      IF(J.EQ.BPWEL) J1 = APWEL
      TQ1 = ABS(CUMQ(J1)-CUMQ(J))
      TQ2 = ABS(CUMQ(J)-CUMQ(J2))
      IF(TQ1.GT..5)TQ1 = 1.-TQ1
      IF(TQ2.GT..5)TQ2 = 1.-TQ2
      CUMQA(KOUNT) = ((TQ1 + TQ2)/2.)*ABS(Q(IOUT)/Q(IN))
   10 CONTINUE
      IF(KOUNT.LE.2) GO TO 45
      KNTM1 = KOUNT - 1
      DO 17 L = 2,KNTM1
      L1 = L + 1
      DO 15 LL = L1,KOUNT
      IF(YEARFA(L).LE.YEARFA(LL)) GO TO 15
      TY = YEARFA(L)
      CY = CUMQA(L)
      YEARFA(L) = YEARFA(LL)
      CUMQA(L) = CUMQA(LL)
      YEARFA(LL) = TY
      CUMQA(LL) = CY
   15 CONTINUE
   17 CONTINUE
      YEARFA(1) = YEARFA(2)
      CUMQA(1) = 0.
      DO 20 M = 2,KOUNT
      CUMQA(M) = CUMQA(M) + CUMQA(M-1)
   20 CONTINUE
      KOUNT1 = KOUNT + 1
      DELTYF = YEARFA(KOUNT)-YEARFA(1)
      YEARFA(KOUNT1) = YEARFA(KOUNT) + .2*DELTYF
      CUMQA(KOUNT1) = CUMQA(KOUNT)
      YRMAX = YEARFA(KOUNT1)
      YRMIN = YEARFA(1) - .2*DELTYF
      CALL SET(.27,.87,.27,.87,YRMIN,YRMAX,0.,1.0,1)
      CALL LABMOD(6H(F8.2),6H(F8.2),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,YRMIN,0.)
      CALL CURVE(YEARFA,CUMQA,KOUNT1)
      ENCODE(38,3205,BTITLE)IOUT,IN
 3205 FORMAT("DISTRIBUTION FROM WELL ",I3," TO WELL ",I3)
      CALL PWRI(512,100,BTITLE,38,2,0,1)
      CALL FRAME
      CUMDIS = CUMQA(KOUNT)*Q(IOUT)
      IF(KOUNT1.EQ.0) GO TO 40
```

```
  20  WRITE(6,3105) J,CUMQ(J)
 3105 FORMAT(1X,"THE CUM FLOW FOR PATH ",I3," IS; ",F10.5)
   25 CONTINUE
      RETURN
      END
      SUBROUTINE WLDSTR
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A7/ KSTOR,KZ,KM
      COMMON /A11/ NWELS,NPTHS
      COMMON /A21/ YEARF,YINIT,XINIT,YFINI,XFINI
      COMMON /A25/ IORIG, IDEST
      COMMON /A26/ NPLOT
      COMMON /A27/ KPWEL
      COMMON /B2/ CUMQ
      REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
      REAL YEARF(80), YINIT(80), XINIT(80)
      REAL YEARFA(82), YFINI(80), CUMQA(82), CUMQ(80), IPOINT(80)
      REAL  XFINI(80), IORIG(80), IDEST(80)
      REAL KPWEL(20), DUMB(10)
      REAL YEARFT(82), CUMQAT(82)
      DIMENSION BTITLE(4)
C
C
C      *******************************************************
C      *                                                     *
C      *  THE PERCENTAGE OF FLUID AT A PUMPING WELL THAT     *
C      *  ORIGINATES AT A GIVEN PUMPING WELL IS DETERMINED.  *
C      *                                                     *
C      *******************************************************
C
C
C
      IF((NPLOT.EQ.4) .OR. (NPLOT.EQ.3)) GO TO 5
      IF((NPLOT.EQ.-4) .OR. (NPLOT.EQ.-3)) GO TO 5
      IF((NPLOT.EQ.6) .OR. (NPLOT.EQ.7)) GO TO 5
      IF (NPLOT .EQ. 9) GO TO 5
      RETURN
   5  BPWEL = 0.
      DO 50 IOUT = 1,NWELS
      IF(Q(IOUT).LE.0.) GO TO 50
      APWEL = BPWEL + 1.
      BPWEL = APWEL - 1. + KPWEL(IOUT)
      DO 45 IN = 1,NWELS
      IF(Q(IN).GE.0.) GO TO 45
      KOUNT = 1
      DO 10 J=1,KM
      IF(IORIG(J).NE.IOUT .OR. IDEST(J).NE.IN) GO TO 10
      KOUNT = KOUNT + 1
   20  WRITE(6,3105) J,CUMQ(J)
 3105  FORMAT(1X,"THE CUM FLOW FOR PATH ",I3," IS; ",F10.5)
   25  CONTINUE
       RETURN
       END
       SUBROUTINE WLDSTR
       COMMON /A1/ X,Y,RWELL,Q,HEAD
       COMMON /A7/ KSTOR,KZ,KM
       COMMON /A11/ NWELS,NPTHS
       COMMON /A21/ YEARF,YINIT,XINIT,YFINI,XFINI
       COMMON /A25/ IORIG, IDEST
       COMMON /A26/ NPLOT
       COMMON /A27/ KPWEL
       COMMON /B2/ CUMQ
       REAL X(20),Y(20),RWELL(20),Q(20),HEAD(20)
       REAL YEARF(80), YINIT(80), XINIT(80)
       REAL YEARFA(82), YFINI(80), CUMQA(82), CUMQ(80), IPOINT(80)
       REAL  XFINI(80), IORIG(80), IDEST(80)
       REAL KPWEL(20), DUMB(10)
       REAL YEARFT(82), CUMQAT(82)
       DIMENSION BTITLE(4)
C
C
C       *************************************************
C       *                                               *
C       *  THE PERCENTAGE OF FLUID AT A PUMPING WELL THAT     *
C       *  ORIGINATES AT A GIVEN PUMPING WELL IS DETERMINED.  *
C       *                                               *
C       *************************************************
C
C
C
       IF((NPLOT.EQ.4) .OR. (NPLOT.EQ.3)) GO TO 5
       IF((NPLOT.EQ.-4) .OR. (NPLOT.EQ.-3)) GO TO 5
       IF((NPLOT.EQ.6) .OR. (NPLOT.EQ.7)) GO TO 5
       IF (NPLOT .EQ. 9) GO TO 5
       RETURN
    5  BPWEL = 0.
       DO 50 IOUT = 1,NWELS
       IF(Q(IOUT).LE.0.) GO TO 50
       APWEL = BPWEL + 1.
       BPWEL = APWEL - 1. + KPWEL(IOUT)
       DO 45 IN = 1,NWELS
       IF(Q(IN).GE.0.) GO TO 45
       KOUNT = 1
       DO 10 J=1,KM
       IF(IORIG(J).NE.IOUT .OR. IDEST(J).NE.IN) GO TO 10
       KOUNT = KOUNT + 1
```

```
      JLIM = 82/KOUNT1
      JJ = 0
      DO 30 I = 2,KOUNT1
      IM1 = I - 1
      YRS = (YEARFA(I)-YEARFA(IM1))/FLOAT(JLIM)
      CQS = (CUMQA(I)-CUMQA(IM1))/FLOAT(JLIM)
      DO 25 J = 1,JLIM
      JJ = JJ + 1
      CUMQAT(JJ) = CUMQA(IM1) + CQS*FLOAT(J)
      YEARFT(JJ) = YEARFA(IM1) + YRS*FLOAT(J)
   25 CONTINUE
   30 CONTINUE
      KOUNT1 = JJ
      DO 35 I = 1,KOUNT1
      YEARFA(I) = YEARFT(I)
      CUMQA(I) = CUMQAT(I)
   35 CONTINUE
      WRITE(6,3210) IOUT, IN
 3210 FORMAT(1X///1X," POLYNOMIAL WELL FLOW DISTRIBUTION ",
     *            "FROM WELL ",I3," TO WELL ",I3/)
   40 CALL POLY(KOUNT1,YEARFA,CUMQA,YRMIN,YRMAX,0.,1.,
     *     DUMA,DUMB)
   45 CONTINUE
   50 CONTINUE
      RETURN
      END
      SUBROUTINE POLY(M,X,Y,XMIN,XMAX,YMIN,YMAX,A,B)
      REAL X(100), Y(100), B(10), X1(100), Y1(100)
C
C
C     **************************************************
C     *                                                *
C     *  SUBROUTINE POLY FITS A POLYNOMIAL REGRESSION  *
C     *  THROUGH VALUES DETERMINED BY WELDSTR.         *
C     *                                                *
C     **************************************************
C
C
C
      MM1 = M - 1
      S = 10000.
      N = 0
    5 N = N + 1
      IF((M-N) .LE. 2) N = N - 1
      IF(N.GT.MM1) N = MM1
      S1 = S
      S = REGR (M, X, Y, N, A, B)
      IF(S.LT.S1 .AND. N.LT.4) GO TO 5
      WRITE(6,3305)
 3305 FORMAT(1X/1X,"Y = A + (B1)(X**1) + (B2)(X**2) ",
     *   "+...+ (BN)(XN**)"//)
      WRITE(6,3310) A
 3310 FORMAT(1X,"WHERE",T10,"A  = ",F15.4)
      DELTX = (X(M) - X(1))/25.
      X(1) = X(1) - DELTX
      DO 10  I = 1, 27
      STEPS = I
      X1(I)= X(1) - DELTX + STEPS*DELTX
      Y1(I) = A
      DO 10 J = 1, N
      Y1(I) = Y1(I) + B(J)*X1(I)**J
   10 CONTINUE
      DO 15 J = 1,N
      WRITE(6,3315)J, B(J)
 3315 FORMAT(1X,T10,"B",I1," = ",F15.4)
   15 CONTINUE
      WRITE(6,3320)S
 3320 FORMAT(1X/1X,"WITH A STND DEV OF S = ",F15.4//)
C
C     ..... PLOT REGRESSION CURVE .....
      CALL SETW(.27,.87,.27,.87,XMIN,XMAX,YMIN,YMAX,1)
      CALL LABMOD(6H(F8.2),6H(F8.2),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,XMIN,YMIN)
      CALL CURVEW(X1,Y1,27)
      CALL FRAME
      RETURN
      END
C        FUNCTION REGR, WHICH CARRIES OUT AN NTH-ORDER POLYNOMIAL
C        REGRESSION ON M DATA POINTS CONTAINED IN THE X AND Y ARRAYS.
C        THE FUNCTION NORMALLY RETURNS THE STANDARD DEVIATION S OF THE POINTS
C        POINTS ABOUT THE REGRESSION CURVE.  THE REGRESSION COEFFICIENTS
C        ARE PLACED IN A AND B(1)...B(N).  HOWEVER, IF THE SIMULTANEOUS
C        EQUATION SOLVING ROUTINE SIMUL ENCOUNTERS A NEAR-SINGULAR
C        MATRIX, THE FUNCTION RETURNS THE VALUE 0.
C
      FUNCTION REGR(M,X,Y,N,A,B)
      REAL C(11,11), SX(20), SYX(10), CYX(10), X(100), Y(100), B(10)
      DATA EPS/ 1.0E-20/
C
C     .... COMPUTE SUMS OF POWERS AND PRODUCTS .....
      NTWO = 2 * N
      NP1 = N + 1
      SY = 0.0
      SYY = 0.0
      DO 1 I = 1,N
      NPI =N + I
      SX(I) = 0.0
      SX(NPI) = 0.0
    1 SYX(I) = 0.0
      DO 3 I = 1,M
      SY = SY + Y(I)
      SYY = SYY + Y(I)**2
      DUM = 1.0
      DO 2  J = 1,N
      DUM = DUM * X(I)
      SX(J) = SX(J) + DUM
    2 SYX(J) = SYX(J) + Y(I)*DUM
      DO 3 J = NP1, NTWO
      DUM = DUM * X(I)
    3 SX(J) = SX(J) + DUM
C
C     ..... COMPUTE COEFFICIENTS C(I,J) ...
      FM = M
      CYY = SYY - SY*SY/FM
      DO 4 I = 1, N
      CYX(I) = SYX(I) - SY*SX(I)/FM
      C(I,NP1) = CYX(I)
      DO 4 J=1,N
      IPJ = I + J
    4 C(I,J) = SX(IPJ) - SX(I)*SX(J)/FM
C
C     ..... CALL ON SIMUL TO SOLVE SIMULTANEOUS EQUATIONS .....
      DET = SIMUL(N, C, B, EPS, 1, 11)
      IF (DET .NE. 0.0) GO TO 6
         REGR = 0.0
          RETURN
C
C     ..... COMPUTE INTERCEPT A AND STANDARD DEVIATION S .....
    6 DUM = SY
      TEMP = CYY
      DO 7 I = 1,N
      DUM = DUM - B(I)*SX(I)
    7 TEMP = TEMP - B(I)*CYX(I)
      A = DUM/FM
      DENOM = M - N- 1
      S = SQRT(TEMP/DENOM)
      REGR = S
      RETURN
C
      END
      FUNCTION SIMUL( N, A, X, EPS, INDIC, NRC )
C
C        WHEN INDIC IS NEGATIVE, SIMUL COMPUTES THE INVERSE OF THE N BY
C        N MATRIX A IN PLACE.  WHEN INDIC IS ZERO, SIMUL COMPUTES THE
```

```
C           N SOLUTIONS X(1)...X(N) CORRESPONDING TO THE SET OF LINEAR
C           EQUATIONS WETH ARGMENTED MATRIX OF COEFFICIENTS IN THE N BY
C           N+1 ARRAY A AND IN ADDITION COMPUTES THE INVERSE OF THE
C           COEFFICIENT MATRIX IN PLACE AS ABOVE.  IF INDIC IS POSITIVE,
C           THE SET OF LINEAR EQUATIONS IS SOLVED BUT THE INVERSE IS NOT
C           COMPUTED IN PLACE.  THE GAUSS-JORDAN COMPLETE ELIMINATION METHOD
C           IS EMPLOYED WITH THE MAXIMUM PIVOT STRATAGY.  ROW AND COLUMN
C           SUBSCRIPTS OF SUCCESSIVE PIVOT ELEMENTS ARE SAVED IN ORDER IN
C           THE IROW AND JCOL ARRAYS REAPECTIVELY.  K IS THE PIVOT COUNTER,
C           PIVOT THE ALGEBRAIC VALUE OF THE PIVOT ELEMENT, MAX
C           THE NUMBER OF COLUMNS IN A AND DETER THE DETERMININANT OF THE
C         COEFFICIENT MATRIX. THE SOLUTIONS ARE COMPUTED IN THE (N+1)TH
C           COLUMN OF A  AND THEN  UNSCRAMBLED AND PUT IN PROPER ORDER IN
C           X(1)...X(N) USING THE PIVOT SUBSCRIPT INFORMATION AVAILABLE
C           IN THE IROW AND JCOL ARRAYS.  THE SIGN OF THE DETERMINANT IS
C           ADJUSTED, IF NECESSATY, BY DETERMINING IF AN ODD OR EVEN NUMBER
C           OF PAIRWISE INTERCHANGES IS REQUIRED TO PUT THE ELEMENTS OF THE
C           JORD ARRAY IN ASCENDING SEQUENCE WHERE JORD(IROW(I)) = JCOL(I).
C           IF THE INVERSE IS REQUIRED, IT IS UNSCRAMBLED IN PLACE USING
C           Y(1)...Y(N) AS TEMPORARY STORAGE.  THE VALUE OF THE DETERMINANT
C           IS RETURNED AS THE VALUE OF THE FUNCTION.  SHOULD THE POTENTIAL
C           PIVOT OF LARGEST MAGNITUDE BE SMALLER IN MAGNITUDE THAN EPS,
C           THE MATRIX IS CONSIDERED THO BE SINGULAR AND A TRUE ZERO IS
C           RETURNED AS THE VALUE OF THE FUNCTION.
C
      DIMENSION IROW(50), JCOL(50), JORD(50), Y(50), A(NRC,NRC), X(N)
C
      MAX = N
      IF ( INDIC.GE.0 ) MAX = N + 1
C
C      .....IS N LARGER THAN 50 .....
      IF ( N.LE.50 ) GO TO 5
      WRITE (6,3505)
 3505 FORMAT( 10HON TOO BIG )
      SIMUL = 0.
      RETURN
C
C     ..... BEGIN ELIMINATION PROCEDURE .....
    5 DETER = 1.
      DO 18 K = 1, N
      KM1 = K - 1
C
C     ..... SEARCH FOR THE PIVOT ELEMENT .....
      PIVOT = 0.
      DO 11 I = 1, N
      DO 11 J = 1, N
C     ..... SCAN IROW AND JCOL ARRAYS FOR INVALID PIVOT SUBSCRIPTS .....
      IF ( K.EQ.1 ) GO TO 9
      DO 8 ISCAN = 1, KM1
      DO 8 JSCAN = 1, KM1
      IF ( I.EQ.IROW(ISCAN) )  GO TO 11
      IF ( J.EQ.JCOL(JSCAN) )  GO TO 11
    8 CONTINUE
    9 IF (ABS(A(I,J)).LE.ABS(PIVOT) )  GO TO 11
      PIVOT = A(I,J)
      IROW(K) = I
      JCOL(K) = J
   11 CONTINUE
C
C     ..... INSURE THAT SELECTED PIVOT IS LARGER THAN EPS .....
      IF (ABS(PIVOT).GT.EPS)  GO TO 13
      SIMUL = 0.
      RETURN
C
C     ..... UPDATE THE DETERMINANT VALUE .....
   13 IROWK = IROW(K)
      JCOLK = JCOL(K)
      DETER = DETER * PIVOT
C
C     ..... NORMALIZE PIVOT ROW ELEMENTS .....
      DO 14  J = 1, MAX
   14 A(IROWK,J) = A(IROWK,J)/PIVOT
C
C     .....CARRY OUT ELIMINATION AND DEVELOP INVERSE .....
      A(IROWK,JCOLK) = 1./PIVOT
      DO 18  I = 1, N
      AIJCK = A(I,JCOLK)
      IF ( I.EQ.IROWK )  GO TO 18
      A(I,JCOLK) = -AIJCK/PIVOT
      DO 17 J = 1, MAX
   17 IF ( J.NE.JCOLK )  A(I,J) = A(I,J) - AIJCK*A(IROWK,J)
   18 CONTINUE
C
C     ..... ORDER SOLUTION VALUES (IF ANY) AND CREATE JORD ARRAY .....
      DO 20  I = 1, N
      IROWI = IROW(I)
      JCOLI = JCOL(I)
      JORD(IROWI) = JCOLI
   20 IF ( INDIC.GE.0 )  X(JCOLI) = A(IROWI,MAX)
C
C     ..... ADJUST SIGN OF DETERMINANT .....
      INTCH = 0
      NM1 = N - 1
      DO 22  I = 1, NM1
      IP1 = I + 1
      DO 22  J = IP1, N
      IF ( JORD(J).GE.JORD(I) )  GO TO 22
      JTEMP = JORD(J)
      JORD(J) = JORD(I)
      JORD(I) = JTEMP
      INTCH = INTCH + 1
   22 CONTINUE
      IF ( INTCH/2*2.NE.INTCH )  DETER = - DETER
C
C     ..... IF INDIC IS POSITIVE RETURN WITH RESULTS .....
      IF ( INDIC.LE.0 )  GO TO 26
      SIMUL = DETER
      RETURN
C
C     ..... IF INDIC IS NEGATIVE OR ZERO, UNSCRAMBLE THE INVERSE
C           FIRST BY ROWS .....
   26 DO 28  J = 1, N
      DO 27  I = 1, N
      IROWI = IROW(I)
      JCOLI = JCOL(I)
   27 Y(JCOLI) = A(IROWI,J)
      DO 28  I = 1, N
   28 A(I,J) = Y(I)
C     ..... THEN BY COLUMNS .....
      DO 30  I= 1, N
      DO 29  J= 1, N
      IROWJ = IROW(J)
      JCOLJ = JCOL(J)
   29 Y(IROWJ) = A(I,JCOLJ)
      DO 30  J = 1, N
   30 A(I,J) = Y(J)
C
C     ..... RETURN FOR INDIC NEGATIVE OR ZERO .....
      SIMUL = DETER
      RETURN
C
C
      END
      SUBROUTINE PIEZ
      COMMON /A1/ X,Y,RWELL,Q,HEAD
      COMMON /A2/ POROS,DEPTH,HYDRK,U
      COMMON /A3/ XMIN, XMAX, YMIN, YMAX
      COMMON /A4/ FLANG, RTANG, TRUNC
      COMMON /A5/ XCIRC, YCIRC
      COMMON /A11/ NWELS, NPTHS
      COMMON /A20/ RINFL
      COMMON /A22/ PI, QSUM
      COMMON /A28/ NTRX, AFORX,ARETX,BFORX,BRETX
      COMMON /A29/ NTRY, AFORY,ARETY,BFORY,BRETY
```

```
*********************** POLLUTE LISTING *************************




       COMMON /A30/ IBND,BNDRY,SLOPE,BINCPT
      COMMON /A31/ XIM,YIM
      REAL XIM(10,20), YIM(10,20)
      REAL BFORX(101), BRETX(101), BFORY(101), BRETY(101)
      REAL AFORX(101), ARETX(101), AFORY(101), ARETY(101)
      REAL X(20), Y(20), RWELL(20), Q(20), HEAD(20)
      REAL XCIRC(21), YCIRC(21)
      REAL Z(31,31)
      REAL BNDRY(10), SLOPE(10), BINCPT(10)
C
C
C     *************************************************************
C     *                                                           *
C     *   THIS ROUTINE PLOTS A PIEZIOMETRIC SURFACE MAP           *
C     *                                                           *
C     *************************************************************
C
C
      R = RINFL
      CONST = 0.
C
      DELTY = (YMAX-YMIN)/30.
      DELTX = (XMAX-XMIN)/30.
      DO 20 I = 1,31
      XP = (DELTX * FLOAT(I)) - DELTX + XMIN
      CALL STRN(NTRX,AFORX,BFORX,1,XP,XP)
      DO 20 J = 1,31
      YP = (DELTY * FLOAT(J)) - DELTY + YMIN
      CALL STRN(NTRY,AFORY,BFORY,1,YP,YP)
      DO 5 K = 1,NWELS
      IF (SQRT((XP-X(K))**2 + (YP-Y(K))**2) .LT. RWELL(K))
     *   YP = Y(K) + RWELL(K)
  5   CONTINUE
      Z(I,J) = (-U) * (XP*COS(FLANG) - YP*SIN(FLANG))
     *         + CONST
      DO 15 L = 1,NWELS
      XX2 = (XP - X(L))**2
      YY2 = (YP - Y(L))**2
      BOT = SQRT(XX2 + YY2)
      UNIT = 1.0
      IF(R .LE. SQRT(XY2)) UNIT = 0.0
      QM = (Q(L))/(2.*PI*DEPTH*HYDRK)*(UNIT)
C
      Z(I,J) = QM * ALOG(R/BOT) + Z(I,J)
C
C
C    ...OPERATE ACROSS BOUNDARY WITH IMAGE WELLS ...
C
```

```
C
C
C     ... READ TRANSMISSIVITY DATA, THEN INVERT ...
      SD2 = (SMAX-SMIN)/2.
      DO 5 I = 1,N
      S(I) = SMIN - SD2 + (SD2 * FLOAT(I))
      P(I) = SQRT(ANIST/ANISB)
    5 CONTINUE
C
C
C
C     ... SIMULATE INTEGRATION (BY SLOPE METHOD), THEN
C         DETERMINE 51 POINTS ALONG THE NEW TRANSFORM
C         FUNCTION ...
C
      NM1 = N - 1
      G(1) = 0.
      DO 10 I = 1,NM1
      PAVE = (P(I) + P(I+1))/2.
      G(I+1) = (S(I+1) - S(I)) * PAVE + G(I)
   10 CONTINUE
      DO 15 I = 1,N
      SR(I) = S(I)
      GR(I) = G(I)
   15 CONTINUE
      CALL SETW(.27,.87,.27,.87,S(1),S(N),G(1),G(N),1)
      CALL LABMOD(6H(F8.0),6H(F8.0),9,9,1,1,0,0,0)
      CALL GRIDAL(5,5,5,5,1,1,5,S(1),0.)
      CALL CURVEW(S,G,N)
      CALL FRAME
      RETURN
      END
      SUBROUTINE STRN(NTRS,H,G,N,SOLD,SNEW)
      REAL SOLD(501), SNEW(501), H(201), G(201)
C
C
C     ********************************************************
C     *                                                      *
C     *  THIS SUBROUTINE TAKES THE FORWARD OR RETURN FUNCTION *
C     *  DETERMINED IN SUBROUTINE VART AND PERFORMS THE      *
C     *  TRANSFORM.                                          *
C     *                                                      *
C     *                                                      *
C     ********************************************************
C
C
      IF(NTRS.NE.0) GO TO 10
      DO 5 I = 1,N
      SNEW(I) = SOLD(I)
    5 CONTINUE
```

```
      IF (IBND .EQ. 0) GO TO 15
      DO 10 L1 = 1,IBND
      IF (SQRT((XP-XIM(L1,L))**2 + (YP-YIM(L1,L))**2) .LT. RWELL(L))
     *    YP = YIM(L1,L) + RWELL(L)
      XX2 = (XP - XIM(L1,L))**2
      YY2 = (YP - YIM(L1,L))**2
      BOT = SQRT(XX2 + YY2)
      QM = BNDRY(L1)*(Q(L))/(2.*PI*DEPTH*HYDRK)*(UNIT)
      Z(I,J) = QM * ALOG(R/BOT) + Z(I,J)
   10 CONTINUE
C
C
   15 CONTINUE
   20 CONTINUE
      CALL CONREC(Z,31,31,31,0.,0.,0.,-1,0,0)
      RETURN
      END
      SUBROUTINE IMAGE(SLOPE,BINCPT,XWELL,YWELL,XIM,YIM)
C
C     **************************************************
C     *                                                *
C     *  THIS ROUTINE LOCATES AN IMAGE WELL ACROSS     *
C     *  A SPECIFIED BOUNDARY                          *
C     *                                                *
C     **************************************************
C
C
      SLOPEP = (-1.)/SLOPE
      DINCPT = YWELL - SLOPEP * XWELL
      XINTER = (DINCPT - BINCPT)/(SLOPE - SLOPEP)
      DELTX = XWELL - XINTER
      XIM = XWELL - 2. * DELTX
      YIM = SLOPEP * XIM + DINCPT
      RETURN
      END
      SUBROUTINE VART(SMIN,SMAX,N,S,G,GR,SR,ANIST,ANISB)
      REAL T(201), S(201), P(201), G(201), GR(201), SR(201)
C
C
C     *****************************************************
C     *                                                   *
C     *  THIS SUBROUTINE PERFORMS TRANSFORMS BETWEEN      *
C     *  A REAL ANISOTROPIC AQUIFER AND AN IMAGINARY      *
C     *  ISOTROPIC ONE.    BOTH FORWARD AND RETURN        *
C     *  TRANSFORMATION FUNCTIONS ARE DETERMINED.         *
C     *                                                   *
C     *****************************************************
C
```

```
    GO TO 25
 10 M = NTRS - 1
    DO 20 I = 1,N
    JH = 1
    DO 15 J = 1,M
    IF (SOLD(I) .GE. H(J)) JH = J
 15 CONTINUE
    A = H(JH)
    B = H(JH+1)
    C = G(JH)
    D = G(JH+1)
    SNEW(I) = ((SOLD(I)-A)*(D-C)/(B-A)) + C
 20  CONTINUE
 25 RETURN
    END
```

APPENDIX C

AQUEOUS CHEMICAL ANALYSIS FOR 24 GEOTHERMAL WATER SAMPLES FROM 19 WELLS AND HOT SPRINGS

(Units; solutes ppm or mg/l; gases ml/lor vol. %)

Raft River, KGRA

Well ID	RRGE 1	RRGE 1	RRGE 2	RRGE 3	RRGE 1	RRGE 2	RRGE 3	RRGI 6
Well Sample Depth	1521 m		1825 m		1520 m	1994 m	1804 m	1176 m
Date	2/6/76	3/23/75						
Temp	96°C	160 PSI	96°C	88°C	141°C	144°C	149°C	71°C
Eh	<-210	red.						
pH	7.23		7.74	6.80	7.3	7.6	7.2	7.3
SpC	2800.							
TDS		1319.		5664.	1650	1290	4100	6380
Salinity	1715.							
Temp (downhold or geothermometer)	146°C	166°C 133°qtz	147°C	148°C				
As	--		<.05					
Al	tr.		tr.					
B	0.2	0.3	.25					
Ba	<.4	<.4	<.4					
Be	<.002		<.0001					
Ca	57.	52.0	48.	280.	56	35	178	214
Cd	--							
Co	--							
Cr	tr.		tr.					
Cu	tr.		tr.					
Fe	0.32	3.2	--					
K	26.7	25.0	36.3	43.	34	38	105	32
Li	1.25	1.1	1.2	3.9	1.6	1.1	3.1	5.1
Mg	0.76	1.9	1.23	2.7	.6	0.13	0.5	1.4
Mn	0.07	.08	.06					
Na	400.	368.	433.	1790	472	441	1194	2100
Ni	3.7	3.5	3.6					
Pb	tr.		tr.					
P	0.016	<.003	.01					
Si	46.	44.	59.3	43.				
Sn	--							
Sr	1.44	1.3	1.37	8.7				
Ti	tr.		tr.					
V	--							
Zr	tr.		tr.					
Zn	--							
Cl	614.	611.0	804.	3310	832	681	2260	2640
Br	<2.5	<2.5	<1.5					
I	0.036	.035	0.053					
F	5.4	5.5	7.64	4.4	5.6	8.7	4.9	7.1

(continued)

APPENDIX C (continued)

	Raft River							
PO_4	.05							
SO_4	61.	63.	53.	67.	36	53	60	60
$S^=$	<.2	<.2	<.1					
NO^-_3	.44	.19						
HCO^-_3	45.4	86.6	63.6	40.6	41	90	44	73
CO_3	8.8	--	16.1	—				
SiO_2	102	91.8	129	114.	184.	156	165	94
NH^+_4	1.99	4.53	.33	.15				
$Si(OH)_4$	167.2		193.7					
H_2	.28							
He	.02	.07						
N_2	50.5	81						
O_2	.06	.25						
Ar	.86	1.7						
CO_2	.5							
STP Total gas	56.7							
Au								
Bi								
Rb								
CH_4	.167							
NAR	19.5							
Cs								
Hg								
Ag								
Mo								
Mo								
Ce								
Ge								
Nb								
Source (see References Sec. 9)	6	6	6	6	26	26	26	26

(continued)

APPENDIX C (continued)

Roosevelt Hot Springs, KGRA

Well ID	54-3	54-3	55-3	72-16	R Hot Sp	R. Seep
Well Sample Depth						
Date	1977	11/11/75	5/25/75	1/29/77	9/11/75	8/15/75
Temp	260		205	92	55	28
Eh	≤-200*	≤-210*	≤-180*	≤-70		
pH	6.5	6.9/7.0	6.3	5	7.9	7.5
SpC		1100			13200	
TDS	6442	6700	7067	6572	7860	5948
Salinity						
Temp Downhole or geoth	294		273		283	239
As	1.8	3.8	2.4			.8
Al						
B	29	28	25	25	38	29
Ba	.46	<.4	0			1.19
Be						
Ca	10.1	7	8	31	22	107
Cd						
Co						
Cr			5			
Cu						
Fe	5.3	0.2	0	0.16		3.2
K	410	400	448	403	488	280
Li	19	20	20	20	.27	17
Mg	.24	0.1	.01	.26	0	23.6
Mn		<.2				
Na	2000	2000	2437	2072	2500	1800
Ni						
Pb						
P						
Si						
Sn						
Sr	5	<5	5			6
Ti						
V						
Zr						
Zn						
Cl	3400	3600	4090	3532	4240	3200
Br		<5	5		3.3	
I						
F	5	6	5		7.5	3.3

(continued)

APPENDIX C (continued)

	Roosevelt Hot Springs, KGRA					
PO_4						
SO_4	54.4	55	59	48	73	70
$S^=$						
NO^-_3	tr.	tr.	0.1		11	tr.
HCO^-_3	200	200	180	25	156	300
CO_3	0	0	0			0
SiO_2	480	300	506	639	313	107
NH^+_4	0.1	<1	0.7			.11
$Si(OH)_4$						
H_2	.28					
He	.02	.07				
N_2	50.5	81				
O_2	.06	.25				
Ar	.86	1.7				
CO_2	.5					
STP Total gas	56.7					
Au						
Bi						
Rb		3.9				
CH_4						
NAR						
Cs		3.1				
Hg						
Ag						
Mo						
Mo						
Source (see References Sec. 9)	18	18	18	18	18	

(continued)

APPENDIX C (continued)

East Mesa, KGRA

Well ID Well Sample Depth Date	MESA 5-1 (801) well head 5/74	MESA 6-1 (802) well head 6/76	MESA 6-2 (803) well head 3/76	MESA 8-1 (804) well head 6/76	MESA 31-1 (805) well head 6/76
Temp	131	166	--	--	--
Eh		red	red	red	red
pH	9.12	5.45	6.12	6.27	6.27
SpC		40000	6000	3200	4700
TDS	1575	26300	5000	1700	2900
Salinity					
Temp Downhole or geoth					
As		.26	.22	.053	.025
Al		.04	.03	.02	.02
B		9.75	7.45	1.6	2.5
Ba		14	.25	.15	.15
Be		<.02	<.02	<.02	.15
Ca	16.2	1360	16.4	8.5	8.9
Cd		<.01	<.01	<.01	<.02
Co		.06	<.01	<.01	<.01
Cr		<.01	<.02	<.01	<.01
Cu		<1	<.01	<1	<1
Fe		8.8	<.1	<.1	<.1
K	29	1050	150	70	85
Li		40	4	1.1	.6
Mg	2.1	17.2	.24	<.05	<.05
Mn		.95	.05	<.05	<.05
Na	593	8100	1700	610	730
Ni		.1	<.1	<.1	<.1
Pb		<.5	<.5	<.5	<.5
P					
Si					
Sn					
Sr			6.5	2.1	1.4
Ti			<.1	<.1	<.1
V			<.005	<.005	<.005
Zr					
Zn			<.01	<.01	<.01
Cl	454	15850	2124	500	510
F		.99	1.23	1.6	1.42

(continued)

APPENDIX C (continued)

	East Mesa, KGRA				
PO_4		.99	1.23	1.6	1.42
SO_4	102	42.8	156	173	183
$S^=$			1.5	1	.3
NO^-_3		<.02	.1	.34	.43
HCO^-_3	331.5	202	560	417	845
CO_3					
SiO_2	201	320	269	389	274
NH^+_4		40.75	14.7	4.95	2.45
$Si(OH)_4$					
H_2					
He					
N_2					
O_2					
Ar					
CO_2					
STP Total gas					
Au		<.01	<.01	.024	.08
Bi		3.	<.005	<.005	<.005
Rb		3.9			
CH_4					
NAR					
Cs		3.1			
Hg		<.002	<.002	<.014	<.008
Ag		<.013	<.01	<.01	<.01
Mo					
Mo		<.005	<.005	<.005	<.005
Ce		2.75	.38	.14	.2
Ge		<.01	<.1	<.1	<.1
Nb		.4	.4	.4	.4
Source (see References Sec. 9)	15	15	15	15	15

(continued)

APPENDIX C (continued)

	Klamath Falls		Salton Sea		
Well ID	WELL #6 OIT	LISKEY WELL	EE ELMORE #1 (806)	IMP PROD IID 3 (810)	MPC MAGMAMAX #1 (811)
Well Sample Depth					
Date	3/31/75	5/9/74	--	3/65	3/74
Temp					
Eh			red		red
pH	8.2	8.9	4.9	7.5	6.10
SpC	1050	1030		47.6K	22697
TDS	7700	724	318K	35.96K	203.4K
Salinity					
Temp Downhole or geoth					
As				.16	.187
Al			<15	2	
B	1.0	.65	350	100	
Ba			480	3	55.7
Be					.08
Ca	24.2	15	31.5K	1130	23.6K
Cd					1.12
Co					
Cr					0.3
Cu			12		
Fe			2500	.7	
K	3.9	4.0	20.8K	1250	7960
Li			270	40	1.4
Mg	0.1	0.1	16	74	110
Mn			570	6.4	
Na	195	200	62.8K	10.6K	47.3K
Ni					
Pb			100		36.2
P					
Si					
Sn					
Sr			1050	85	102.4
Ti					
V					
Zr					
Zn					283
Cl	58	59	185K	19.7K	123390
Br				15	
I				4.5	
F	1.45	1.5		1	12

(continued)

APPENDIX C (continued)

	Klamath Falls		Salton Sea		
PO_4					<.8
SO_4	400	2	49	621	<10
$S^=$					
NO^-_3				9.0	1.05
HCO^-_3	44	48	40	574	61.6
CO_3	0	2			
SiO_2	31	90	1050	120	435
NH^+_4				321	570
$Si(OH)_4$					
H_2					
He					
N_2					
O_2					
Ar					
CO_2				29	
STP Total gas					
Au					
Bi					5
Rb					50.4
CH_4					
NAR					
Cs					250
Hg					<.001
Ag					172
Mo					.43
Mo					
Source (see References Sec. 9)	15	15	15	15	15

APPENDIX D

AQUEOUS SPECIES CONCENTRATION RESULTS FOR PHILLIPS GEOTHERMAL WELL 54-3 AT ROOSEVELT HOT SPRINGS KGRA

Species	Charge	Concentration at 100°C (ppm)	Concentration at 25°C (ppm)	Input Concentration (ppm)
Ca	+2	8.99	9.84	10.1
CaOH	+1	6.25 E-4	5.56 E-6	
$CaSO_4$	0	4.60 E-1	4.35 E-1	
$CaHCO_3$	+1	2.37	3.19 E-1	
$CaCO_3$	0	1.43 E-1	4.88 E-3	
Mg	+2	2.24 E-1	2.32 E-1	2.40 E-1
MgOh	+1	2.01 E-4	1.04 E-6	
$MgSO_4$	0	1.50 E-2	1.36 E-2	
$MgHCO_3$	+1	2.08 E-2	1.22 E-2	
$MgCO_3$	0	1.42 E-3	8.88 E-5	
MgF	+1	1.18 E-2	2.93 E-3	
Na	+1	1.99 E+3	1.98 E+3	2.00 E+3
$NaSO_4$	-1	1.06 E+1	8.66	
Na_2SO_4	0	7.67 E-1	3.45	
$NaHCO_3$	0	6.86	7.71	
$NaCO_3$	-1	1.39	4.88 E-2	
Na_2CO_3	0	3.39 E-3	2.56 E-3	
NaCl	0	6.49	7.05	
B	+3	0.00	0.00	2.9 E+1
H_3BO_3	0	1.65 E+2	1.65 E+2	
H_2BO_3	-1	1.35	3.91 E-1	
Ba	+2	4.60 E-1	4.60 E-1	4.60 E-1
BaOH	+1	4.97 E-6	3.40 E-8	
CL	-1	3.40 E+3	3.40 E+3	3.40 E+3
HCO_3	-1	1.87 E+2	1.93 E+2	2.00 E+2
CO_3	-2	9.74 E-2	5.93 E-2	
SO_4	-2	4.21 E+1	4.34 E+1	5.44 E+1
HSO_4	-1	5.53 E-3	6.39 E-4	
H_2SO_4	0	1.33 E-13	1.60 E-13	
F	-1	4.99	5.00	5.00
Fe	+2	5.30	5.30	5.30
SiO_2				4.80 E+2
H_4SiO_4	0	7.63 E+2	7.67 E+2	
H_3SiO_4	-1	4.54	3.71 E-1	
H_2SiO_4	-2	1.45 E-2	5.00 E-6	

APPENDIX E

SUMMARY OF GEOCHEMICAL COMPUTER PROGRAM SPECIFICATIONS

Class I Programs

A. WATEQ, WATEQF (24, 28)*

1. Language: PL1 (WATEQ); FORTRAN (WATEQF)
2. Computers: IBM 370 (WATEQ): IBM 370, CDC 6400/6600, CDC-CYBER 171, DEC-PDP 11-23 (WATEQF)
3. Species (WATEQF): 105 (8 redox) from 21 elements
4. Minerals (WATEQF): 101
5. Gases: 3
6. Temperature range: 0-100°C
7. Pressure: 1 bar
8. Comments: The original program, WATEQ, uses the 'brute force' (24B) successive approximation method for convergence on anion mass balance and the continued fraction method for cations. WATEQF uses the more rapid continued fraction method for both anion and cation mass balance convergence. WATEQF considers 14 manganese species (redox dependent) and 21 manganese minerals not present in WATEQ. Both programs consider all of the Priority Group I parameters (see Table 9.1), except As and also include Al, Sr, PO_4, and NO_3.

B. WATEQ2 (2)

1. Language: PL1 optimizing
2. Computers: IBM 370, Honeywell 60/68/80
3. Species: 200 (12 redox) from 31 elements
4. Minerals: 309
5. Gases: 3
6. Organics: 12 metal complexes
7. Temperature range: 0-100°C
8. Pressure: 1 bar
9. Comments: Includes all parameters on text Table 9.1, except Be, Sb, and Se. Reaction thermodynamic data base contains over 450 speciation and mineral reactions, updated in 1980 (17B). Uses continued fraction calculation scheme for cation and anion mass balance convergence.

*References in Section 9

C. SOLMNEQ (19)
   1. Language: PL1
   2. Computers: IBM 360/370
   3. Species: 181 (12 redox) from 26 elements
   4. Minerals: 158
   5. Gases: 3
   6. Organics: 10 metal complexes
   7. Temperature range: 0-350°C
   8. Pressure Range: 1-1000 bars
   9. Comments: Uses continued fraction convergence method for anions and cations. Calculates the silica and Na-K-Ca geothermometers and ion exchange equilibria. Includes all parameters from text Table 9.1 except Cd, Cr, Ni, I, Sb, Se, and Mo.

Class II Programs

A. MIX2 (23)
   1. Language: FORTRAN
   2. Computers: IBM 370, CDC 6400, CDC-CYBER 171, DEC-PDP 11-03
   3. Species: 30 (no redox) from 9 elements
   4. Minerals: 8
   5. Temperature range: 0-100°C
   6. Pressure: 1 bar
   7. Comments: Uses continental fraction method for aqueous speciation convergence and either parabolic approximation or interval halving root finding methods to find pH after each mass transfer step. Simulates mixing, titration, and solution/precipitation for one mineral phase at a time. MIX2 considers only common minerals and major aqueous constituents and does not include As, B, Fe, Li, Mn, F, SiO_2, or NH_4 from the Priority Group I parameters listed in Table 9.1.

B. PHREEQE (22)
   1. Language: FORTRAN
   2. Computers: IBM-AMDAHL 470V/7, CDC 6400, CDC-CYBER 171
   3. Species: input dependent
   4. Minerals: input dependent
   5. Gases: input dependent
   6. Temperature range: reaction modeling can probably be accomplished from 0-350°C upon input by experienced geochemists.
   7. Pressure: input dependent
   8. Comments: PHREEQE is a derivative of WATEQF and MIX2. It uses the continued fraction method for speciation convergence coupled with Newton-Ralphson matrix solutions

for convergence on Eh and pH after mass transfer steps. PHREEQE can simulate mixing, titration, evaporation, and a number of concomitant mineral, gas, and ion exchange mass transfers. The numbers and types of mass transfers used are practically unlimited in terms of foreseeable applications to natural systems. This program is a very sophisticated predictive chemical modeling tool.

C. EQ3/6 (32)
  1. Language: FORTRAN
  2. Computers: CDC 6400/6600/7600
  3. Species: 140 (14 redox) from 20 elements
  4. Minerals: 130
  5. Gases: 8
  6. Temperature range: 0-300°C
  7. Pressure range: steam saturation or 500 bars
  8. Comments: Uses continued fraction method modified with calculation stability constraints to ensure speciation convergence over a wide range of solution chemistries. Uses a finite difference-Newton Raphson, predictor-corrector method for convergence on Eh and pH after mass transfers. Simulates mixing, titration, and mass transfers for multiple mineral, gas, and ion exchange reactions. EQ3/6, like PHREEQE, is also a sophisticated tool, the primary differences being that EQ3/6 employs different numerical methods and has a series of thermochemical constant data bases already specified.

APPENDIX F

AQUEOUS CHEMICAL ANALYSIS USED FOR FIGURES 9.3 and 9.4

Constituent		Steamboat Spring NV	Martis Warm Spring CA	Fallon Water Supply NV
T (°C)		81		
pH		6.75	8.51	8.67
HCO_3	(mg/l)	280	128	275
Cl	"	850	6.7	76.38
SO_4	"	155	4.6	80.1
Na	"	630	20.54	180.04
K	"	69.6	8.078	7.277
Ca	"	7.17	18.75	1.648
Mg	"	0.32	4.058	.4511
Li	"	8.1		
SiO_2	"	129		